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GEOLOGY OF THE FREMONT PEAK AND OPAL MOUNTAIN QUADRANGLES, CALIFORNIA

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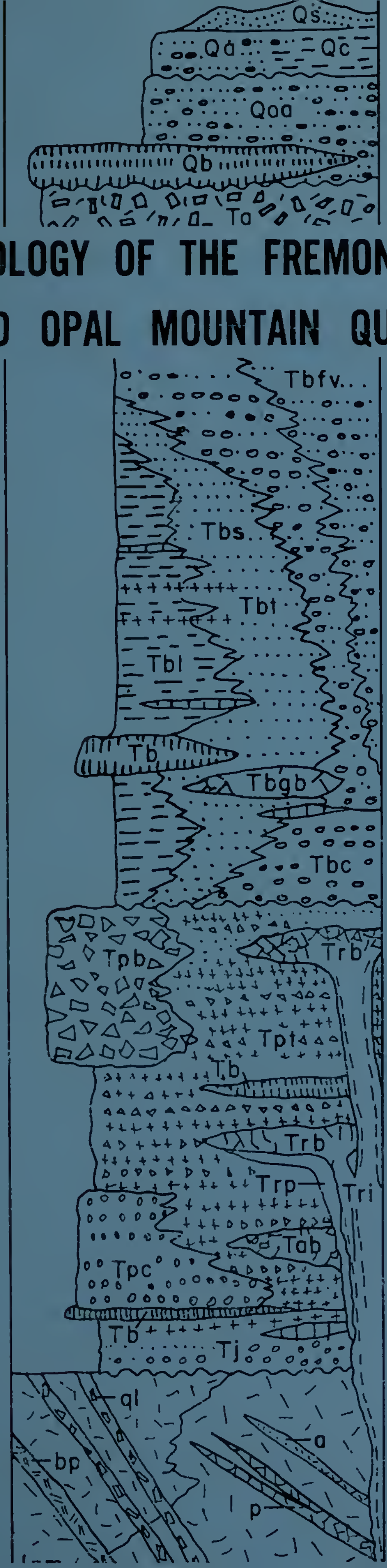

BULLETIN 188

CALIFORNIA DIVISION OF MINES AND GEOLOGY
FERRY BUILDING, SAN FRANCISCO, 1968

GEOLOGY OF THE FREMONT PEAK AND OPAL MOUNTAIN QUADRANGLES, CALIFORNIA

By T. W. DIBBLEE JR.

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ABSTRACT

The Fremont Peak and Opal Mountain 15-minute quadrangles together cover about 490 square miles in the west central Mojave Desert in northwestern San Bernardino County. The center of the area is 20 miles northwest of Barstow. The area includes Harper Valley, Fremont Peak, Opal Mountain, Black Mountain, Williams Plain, and the Mud Hills. Altitudes above sea level range from 2,020 feet at Harper Dry Lake to 4,584 feet at Fremont Peak.

The rock units of the area may be grouped into three major divisions separated by profound unconformities. These divisions are: pre-Tertiary crystalline rocks; Tertiary nonmarine sedimentary and volcanic rocks; and Quaternary alluvial sediments and volcanic rocks.

Rocks of pre-Tertiary age consist of plutonic rocks that enclose pendants of metamorphic rocks, and together these rocks form the crystalline basement complex upon which rest the Cenozoic formations. The metamorphic rocks are of supposed Precambrian age and consist of gneisses which in places contain thin intercalations of marble. The plutonic rocks are of presumably Mesozoic age and consist mainly of quartz monzonite, and local masses of granodiorite, quartz diorite, hornblende diorite, and dikes of pegmatite and aplite. In general the sequence of intrusion is from mafic to silicic rocks. Dikes of felsitic to porphyritic rocks, mainly of quartz latite of late Cretaceous or possibly early Tertiary age, cut the plutonic and metamorphic rocks in the western part of the area.

The series of Tertiary terrestrial pyroclastic and sedimentary rocks, including several basalt flows, attains a maximum thickness of about 6,000 feet, and consists of the following units in ascending order: Jackhammer Formation, 0–150 feet of sandstone, basalt and tuff, lower Miocene(?); Pickhandle Formation, 0–2,800 feet of tuff and breccia, middle(?) Miocene; and Barstow Formation, 0–4,500 feet of fanglomerate, sandstone and shale, late middle and upper Miocene. Tertiary volcanic rocks include the Opal Mountain Volcanics, mostly quartz latite that is associated with the Pickhandle Formation as intrusive and extrusive bodies; and several extrusive bodies of the Lane Mountain Andesite, Pliocene(?), that rest upon the eroded surface of the pre-Tertiary crystalline rocks in the eastern part of the area.

Formations of Quaternary age, which rest unconformably on the Tertiary and pre-Tertiary rocks, consist of as much as several hundred feet of alluvial gravel, sand and clay that fill all the valley areas, and an extensive flow of basalt mapped as the Black Mountain Basalt, Pleistocene.

The pre-Tertiary crystalline rocks crop out west of Harper Valley and in the northern and extreme southeastern parts of the map area. The Tertiary rocks fill an ancient elongated downwarp trending west-northwesterly across both quadrangles. The area is cut by three major northwest-trending fault zones: the Lockhart fault zone crossing the extreme southwestern portion; the Harper fault zone across the central portion; and the Blackwater-Mud Hills fault zone crossing the northeastern portion. All are high angle faults with small apparent vertical displacements, and all involve Quaternary formations. The 7-mile-wide block between the latter two fault zones is an unstable one in which the Tertiary formations, and to a lesser extent the overlying Quaternary basalt, are deformed into folds with axes trending east-west. The folds of this block are more strongly compressed adjacent to the two major fault zones and are probably subsidiary to them. The east-trending axes suggest right-lateral displacements of the underlying basement complex along the fault zones. The blocks northeast and southwest of this unstable block are relatively stable and consist of crystalline rocks that are overlain by thin mantles of undeformed Cenozoic, mostly Quaternary, formations.

Mineral resources within the area consist of pumicite, perlite, and quartz, of which small amounts have been quarried; placer gold and strontianite, of which subcommercial amounts have been produced.

GEOLOGY OF THE FREMONT PEAK AND OPAL MOUNTAIN QUADRANGLES, CALIFORNIA *

By T. W. DIBBLEE, JR.

INTRODUCTION

Field Work. The geology of the Opal Mountain and Fremont Peak quadrangles was mapped by the writer during the winters of 1950 and 1951. About five weeks in the field was spent mapping the geology of each quadrangle. In addition the area was visited several times in 1952 and 1953 to check critical localities.

Field work consisted of plotting the geology on aerial photographs issued by the U.S. Army, on scale of about 3 inches per mile for the Opal Mountain quadrangle and about 1¾ inches per mile for the Fremont Peak quadrangle. Because no topographic base maps had been issued for these two quadrangles, a geologic map was prepared after completion of field work from the aerial photographs, which were mosaiced together. The geology was subsequently traced from this map onto the topographic base maps of the Fremont Peak and Opal Mountain quadrangles issued by the U.S. Geological Survey in 1955 and 1956.

Acknowledgments. For leave that made field work possible in 1950 and 1951 the writer is indebted to the Richfield Oil Corporation through the cooperation of Rollin Eckis and M. L. Hill.

The writer is greatly indebted to D. Foster Hewett of the U.S. Geological Survey, who recommended mapping the area because of its well exposed Tertiary formations; who loaned aerial photographs upon which to plot the geology, and thus made the work possible at the time; who directed the work; and who spent several days in the field with the writer. For helpful suggestions the writer is also indebted to T. H. McCulloh, F. M. Byers, G. E. Lewis, W. C. Smith, J. M. McAllister, and R. W. Schmidt, all of the U.S. Geological Survey. Each spent several days field checking and sampling with the writer in the Mud Hills and Black Canyon-Gravel Hills area in 1952.

Acknowledgments are also due to C. E. Tedford and C. H. Scholtz for mammalian fossils collected in the Mud Hills and Black Canyon. For age determination, the writer acknowledges the cooperation of the U.S. Geological Survey: G. E. Lewis determined the age significance of vertebrate fossils collected by Chester Stock of the California Institute of Technology, and others by Tedford and Scholtz; K. E. Lohman collected diatom remains from Black Canyon and the Mud Hills and determined their age significance. Mr. Lewis' description of the stratigraphic paleontology of the Barstow Formation in the Mud Hills area appears on page 34 of this report. Mr. Lohman's description of Miocene diatoms from the Black Canyon area appears on page 35.

The writer is indebted to T. H. McCulloh, who determined the mineral content of a metamorphic limestone; and to R. D. Allen of the U.S. Geological Survey, who determined the mineral content of several samples of igneous rocks from the mapped area.

Previous Geologic Work. The geology of scattered parts of the west central Mojave Desert, within which lie the Fremont Peak and Opal Mountain quadrangles, has been described in a number of publications. Most of these briefly describe the geology of areas just outside the two mapped quadrangles, and are accompanied by small-scale reconnaissance geologic maps.

The earliest account of the geology of the west central Mojave Desert region was by O. E. Hershey (1902, p. 242–372) in which he described and named as the "Barstow series" the flat-lying sediments exposed on the low hills on the north side of the Mojave River valley between Barstow and Daggett.

The earliest description of the Tertiary strata of the "Barstow syncline" (Mud Hills) was by Baker (1911, p. 345–347). He referred these strata to the "Rosamond series," named earlier by Hershey (1902, p. 342–372). Baker (1911, p. 333–383) also discussed the late Cenozoic history of the western Mojave Desert.

Pack (1914, p. 144–145, pl. 1) made brief statements on the crystalline rocks and Cenozoic sedimentary and volcanic rocks north and west of Barstow, and showed a small scale reconnaissance geologic map of the hills surrounding Harper Valley.

J. C. Merriam (1915, p. 253–54; 1919, p. 437–585) collected vertebrate fossils from the strata of the Barstow syncline, determined the fauna to be upper Miocene, and named the strata containing it the "Barstow Formation."

The geology of the Randsburg 15-minute quadrangle, adjacent northwest of the Fremont Peak quadrangle, was described and mapped by C. D. Hulin (1925,

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* Manuscript submitted for publication December 1957; minor text revisions to December 1963.

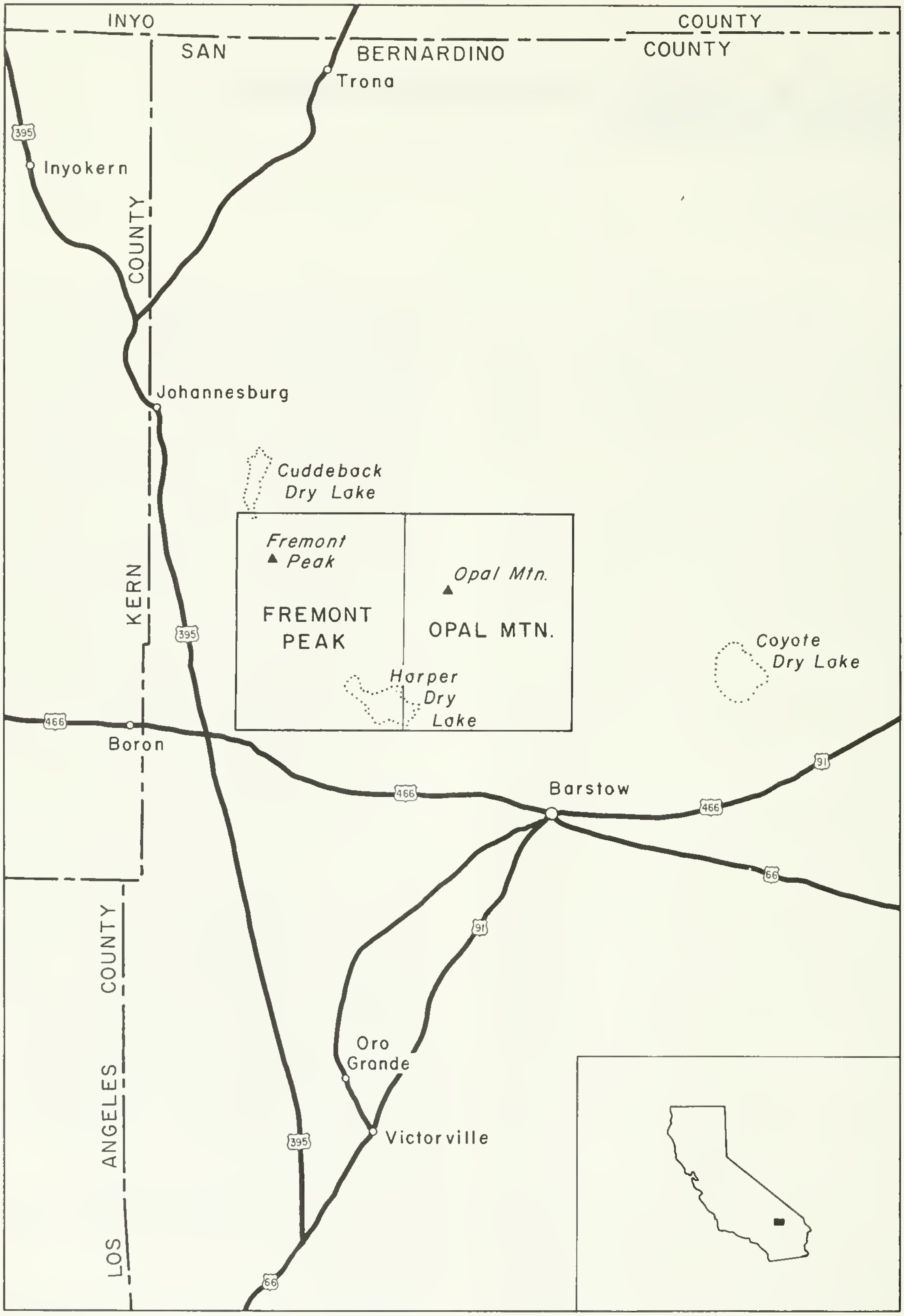


Figure 1. Index map showing location of Fremont Peak and Opal Mountain quadrangles.

p. 1–68, map). This was the first semidetailed geologic work published on the western Mojave Desert region.

The gound-water conditions of Harper and Superior Valleys were described by Thompson (1929, p. 248–49, 268–76) along with data on all water wells drilled, and analyses of water from some. Also included was a reconnaissance geologic map of the area.

The generalized geology of the mapped area shown on the 1938 Geologic map of California (Jenkins, 1938) was based on unpublished work done many years ago by C. D. Hulin.

Several papers have appeared that deal with the geology and mineral deposits of the Kramer borate district, which lies a few miles west of the mapped area. The borate deposits were described by Noble (1926, p. 45–61) and Schaller (1930, p. 137–170); the geology was described and mapped by Gale (1946, p. 325–378).

The regional geology of the Newberry and Ord Mountains, 30 miles southeast of the mapped area, was described by Gardner (1940, p. 257–292); that of the southern Calico Mountains, 10 miles southeast of the mapped area, by Erwin and Gardner (1940, p. 293–304).

The regional geology of parts of the 30-minute Barstow quadrangle, just south of the mapped area, including the Hinkley area, has been described by Miller (1944, p. 73–129).

During recent years much geologic work was done in the west central Mojave Desert. This includes descriptions of some of the mineral deposits within the mapped area by Wright et al. (1953, p. 165, 188, 190); detailed description and geology of the strontianite deposits in the eastern Mud Hills, Opal Mountain quadrangle, by Durrell (1953, p. 23–36, pls. 2–7); geology and mineral deposits of the Barstow 30-minute quadrangle by Bowen (1954, p. 1–205); and distribution and genesis of the major faults throughout the Mojave Desert by Hewett (1954). Besides these published reports and maps, geologic work on nearly all quadrangles surrounding the mapped area has been in progress by U.S. Geological Survey geologists, who have published some preliminary results. This work includes the geology and mineral deposits of the Lane Mountain and north half of the Daggett quadrangle by T. H. McCulloh; geology of the Lava Mountains (Cuddeback Lake quadrangle) by G. I. Smith; geology of the Boron quadrangle (Dibblee 1959); Hawes quadrangle (Dibblee 1960a); and Barstow 15-minute quadrangle (Dibblee 1960b).

GEOGRAPHY

Location. The Fremont Peak and Opal Mountain quadrangles cover about 490 square miles in the west central Mojave Desert, northwestern San Bernardino County, California, between 35°00′ and 35°15′ north latitude and 117°00′ and 117°30′ west longitude.

Culture and Accessibility. The town nearest to the mapped area is Barstow, with a population of about 10,000—a town with important railroad and highway junctions—located about 6 miles south of the southeast corner of Opal Mountain quadrangle. The railroad siding of Hinkley lies 4 miles south of Opal Mountain quadrangle and 11 miles west of Barstow. The only settlement within the mapped area is Lockhart Ranch, the center of a thriving 5,000-acre alfalfa-raising and cattle-feeding project, established by L. M. Lockhart in Harper Valley in the southeastern portion of Fremont Peak quadrangle. Coolgardie Camp, deserted since 1940, is the center of a group of small gold-placer workings in the low hills east of Harper Valley in eastern Opal Mountain quadrangle. About 3 miles north of Coolgardie Camp a pumice quarry has been active. Perlite quarrying operations are also being carried on intermittently in upper Black Canyon near Opal Mountain.

The mapped area is easily accessible by many roads. With the exception of a paved road to Lockhart Ranch, all are dirt roads leading from U.S. Highway 466, which passes a few miles south of the mapped area between Mojave and Barstow, and U.S. Highway 395, which passes a few miles west of Fremont Peak quadrangle, between Adelanto and Johannesburg.

Climate. The climate of this desert region is arid. Average annual precipitation is roughly 5 inches in the valley areas and slightly higher in the highland areas. Nearly all precipitation is in the form of rainfall, which falls mostly during the three winter months. Summer thunderstorms occasionally produce heavy showers that sometimes cause flash floods. Severe westerly gales are frequent during the spring months. In the summer the daytime temperatures generally exceed 100° F.; winter night time temperatures generally fall below freezing.

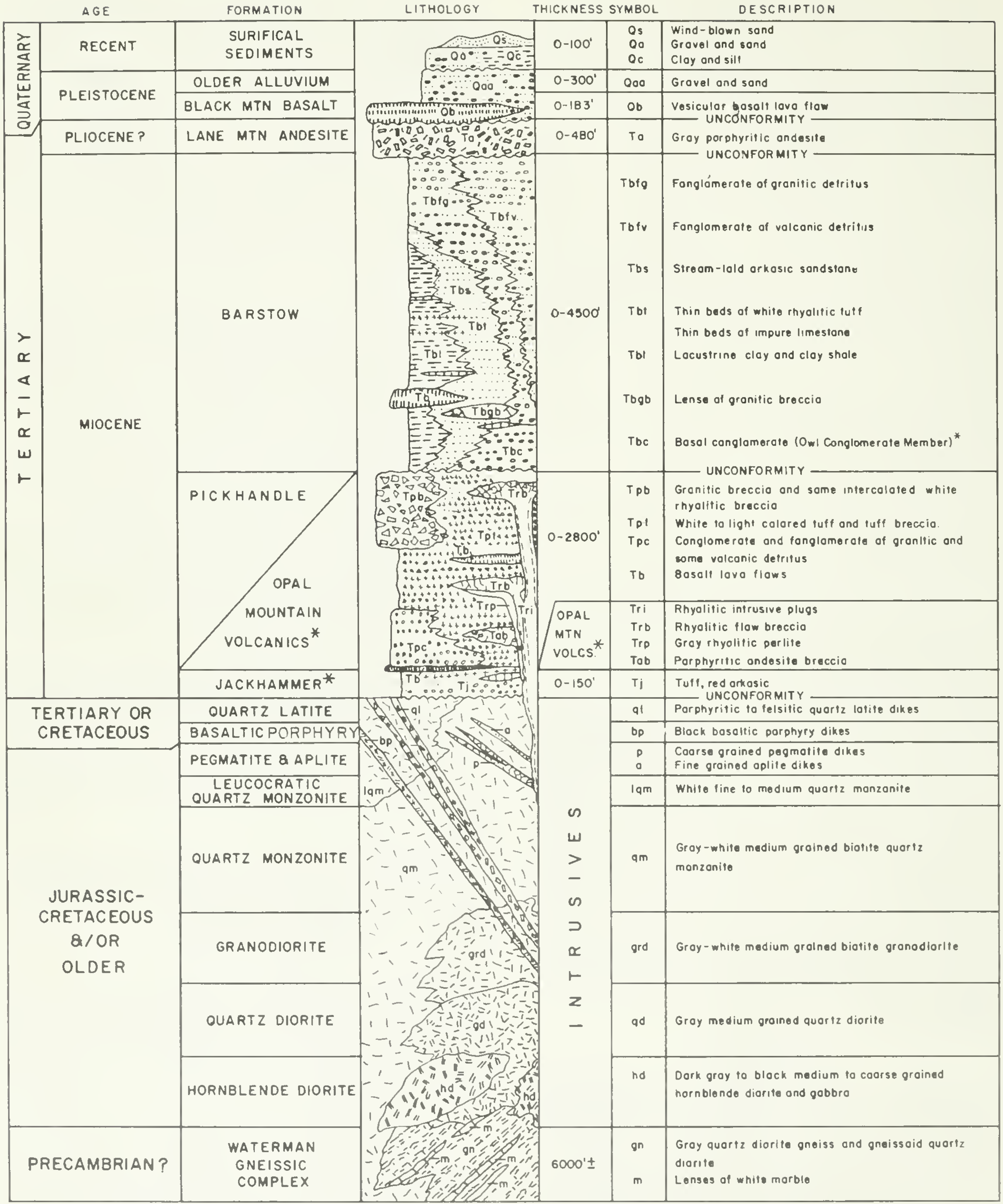
Vegetation. The vegetation of the area is largely of scant low sagebrush, typical throughout the Mojave Desert region. Creosote bush and Burro bush are the most abundant and widespread types. The various rock formations have little influence on the type of vegetation that grows on them except clays, which are generally devoid of brush. Joshua trees and bunch grass are generally abundant on sandy places at elevations above 3,000 feet.

Topography. Fremont Peak and Opal Mountain quadrangles have low to moderate relief. Altitudes above sea level vary from 2,020 feet at Harper Dry Lake to 4,584 feet at Fremont Peak.

ROCK UNITS

The rocks of the two mapped quadrangles may be grouped into three main divisions generally present in the western Mojave Desert: granitic and metamorphic rocks of pre-Tertiary age; nonmarine volcanic, pyroclastic, and sedimentary rocks of Tertiary age; and alluvial sediments and a basalt flow of Quaternary age.

The pre-Tertiary rocks are composed largely of granitic intrusives like those of the Sierra Nevada batholith, of Mesozoic age. Quartz monzonite is the most prevalent granitic rock within the mapped area, but masses of granodiorite, quartz diorite, and hornblende diorite are also present, as well as dikes of pegmatite and aplite. The pre-Tertiary metamorphic



AGE		FORMATION	THICKNESS	SYMBOL	DESCRIPTION
QUATERNARY	RECENT	SURIFICAL SEDIMENTS	0-100'	Qs Qa Qc	Wind-blown sand Gravel and sand Clay and silt
	PLEISTOCENE	OLDER ALLUVIUM	0-300'	Qaa	Gravel and sand
		BLACK MTN BASALT	0-183'	Qb	Vesicular basalt lava flow UNCONFORMITY
TERTIARY	PLIOCENE?	LANE MTN ANDESITE	0-480'	Ta	Gray porphyritic andesite UNCONFORMITY
	MIOCENE	BARSTOW	0-4500'	Tbfg	Fanglomerate of granitic detritus
				Tbfv	Fanglomerate of volcanic detritus
				Tbs	Stream-laid arkosic sandstone
				Tbt	Thin beds of white rhyolitic tuff Thin beds of impure limestone
				Tbl	Lacustrine clay and clay shale
				Tbgb	Lense of granitic breccia
				Tbc	Basal conglomerate (Owl Conglomerate Member)* UNCONFORMITY
		PICKHANDLE	0-2800'	Tpb	Granitic breccia and some intercalated white rhyolitic breccia
				Tpt	White to light colored tuff and tuff breccia.
				Tpc	Conglomerate and fanglomerate of granitic and some volcanic detritus
				Tb	Basalt lava flows
		OPAL MOUNTAIN VOLCANICS*	OPAL MTN VOLCS.*	Tri	Rhyolitic intrusive plugs
				Trb	Rhyolitic flow breccia
				Trp	Gray rhyolitic perlite
				Tab	Porphyritic andesite breccia
		JACKHAMMER*	0-150'	Tj	Tuff, red arkosic UNCONFORMITY
TERTIARY OR CRETACEOUS		QUARTZ LATITE	INTRUSIVES	ql	Porphyritic to felsitic quartz latite dikes
		BASALTIC PORPHYRY		bp	Black basaltic porphyry dikes
JURASSIC-CRETACEOUS &/OR OLDER		PEGMATITE & APLITE		p a	Coarse grained pegmatite dikes Fine grained aplite dikes
		LEUCOCRATIC QUARTZ MONZONITE		lqm	White fine to medium quartz monzonite
		QUARTZ MONZONITE		qm	Gray-white medium grained biotite quartz monzonite
		GRANODIORITE		grd	Gray-white medium grained biotite granodiorite
		QUARTZ DIORITE		qd	Gray medium grained quartz diorite
		HORNBLENDE DIORITE		hd	Dark gray to black medium to coarse grained hornblende diorite and gabbro
PRECAMBRIAN?		WATERMAN GNEISSIC COMPLEX	6000'±	gn m	Gray quartz diorite gneiss and gneissoid quartz diorite Lenses of white marble

New stratigraphic names *

Figure 2. Columnar section of the Fremont Peak and Opal Mountain quadrangles.

rocks consist of gneisses with intercalations of marble, all believed to be Precambrian or possibly Paleozoic in age. The whole complex of crystalline rocks is cut by dikes, mainly quartz latite, of probable late Cretaceous age.

The series of Tertiary pyroclastic and sedimentary rocks, which includes several basalt flows, has a maximum thickness of about 6,000 feet. It was deposited in a trough-like basin that extended northwesterly across the two mapped quadrangles. Volcanic rocks consist of rhyolitic intrusive and extrusive masses associated with the principal pyroclastic unit, and several local extrusive masses of andesite that rest on a Pliocene(?) erosion surface cut on the pre-Tertiary rocks.

Rocks of Quaternary age rest unconformably on the Tertiary and pre-Tertiary rocks and are mainly alluvial gravel, sand, and clay that fill all the valley areas to a maximum depth of several hundred feet. Associated with these alluvial sediments is an extrusive lava flow of basalt as thick as 150 feet.

Pre-Tertiary Metamorphic Rocks

WATERMAN GNEISSIC COMPLEX

Distribution and Name. Metamorphic rocks composed mainly of quartz dioritic gneisses and subordinate marble crop out in Fremont Peak quadrangle, in three isolated hills west of Harper Dry Lake. Farther north in the Fremont Peak area are large exposures of gneiss and gneissoid quartz diorite.

Just south of the mapped area, similar gneissic rocks crop out in low hills bordering Hinkley Valley, Barstow quadrangle, and were mapped and described by Miller (1944, p. 77–80, 97–98, pl. VI). He described those containing marble and schist as the Hinkley Valley Complex, and those composed mainly of foliated dioritic and granitic rocks as the Hodge Complex, and considered both to be of probable Precambrian age. These rocks were later mapped and described by Bowen (1954, p. 17–23, pl. 1). Those containing many layers of marble (most of Miller's Hinkley Valley Complex) he did not describe but mapped as the Oro Grande Series, Carboniferous(?). The gneissic hornblende diorite (part of Miller's Hodge Complex) exposed east of Hinkley he mapped as such; the dioritic gneiss (also part of Miller's Hodge Complex), exposed in the Waterman Hills north of Barstow he named the Waterman Gneiss; he considered both these dioritic rocks to be of late Paleozoic age.

After examining all the gneissic rocks in the Hinkley Valley area, the writer is of the opinion that all these, together with those exposed in the Fremont Peak quadrangle, are of the same metamorphic series and can be referred to as a single rock unit. The two names used by Miller (1944) are not applied to this unit, because the name Hinkley is preoccupied (Wilmarth, 1938, p. 959) and the term Hodge Volcanic Series was applied by Bowen (1954, p. 34–36, pl. 1) to the schistose metavolcanic rocks exposed west of Hodge, Barstow quadrangle. The gneissic rocks containing intercalated layers of white marble and mapped as the Oro Grande Series by Bowen (1954, pl. 1) differ from the Oro Grande Series of the type area near Oro Grande, as pointed out by Miller (1944, p. 78), so that this term is inappropriate for the gneissic rocks. The term Waterman Gneissic Complex is hereby applied to all these gneissic rocks, including those with intercalated white marble, exposed in the environs of Hinkley and Harper Valleys.

Topographic Expression. The Waterman Gneissic Complex weathers readily by mechanical separation of grains so that it is not resistant to erosion and does not form prominent outcrops. West of Harper Valley it weathers to low rounded hills, much as the associated granitic rocks. The intercalated layers of white marble are more resistant than the gneiss and crop out as prominent white ledges. In the Fremont Peak area the Waterman Gneissic Complex tends to weather along foliation planes and to form lenticular slablike outcrops and lenticular fragments.

Field Relationships. The relationships of the Waterman Gneissic Complex with the quartz monzonite are described under quartz monzonite.

The structure of the gneiss and intercalated layers of marble in the isolated exposures of the Waterman Gneissic Complex west of Harper Dry Lake and in

Photo 1. Typical outcrop of Waterman Gneissic Complex. View east across Harper Valley.

Photo 2. Outcrop of Waterman Gneissic Complex 3 miles southeast of Fremont Peak.

the southern part of the Fremont Peak range indicates a regional northeast strike with steep southeast dip of the planar foliation. If the gneiss is not isoclinally folded, the Waterman Gneissic Complex is many thousands of feet thick in this area. This regional attitude of the foliation conforms generally with that of the gneiss exposed southeast of Harper Valley near Hinkley and in the Waterman hills.

Lithology. The Waterman gneissic complex exposed in the low hills west of Harper Dry Lake includes banded gneisses, schists, marbles and quartzites, injected rocks such as pegmatites, and some silicified mylonites; gneiss predominates. In the Fremont Peak range, the Waterman Gneissic Complex is composed almost entirely of gneiss and gneissoid quartz diorite.

The gneiss is a dark gray, prominently to faintly banded rock, with fine- to medium-grained interlocking grain texture. The rock is composed of light-colored laminae, from 1 to about 10 millimeters thick, of quartz and feldspar with little or no dark minerals, alternating with darker laminae rich in biotite and hornblende; some laminae are almost entirely of hornblende. The laminae are generally slightly undulating, uneven in thickness or lenticular, and in places resemble cross-bedding. Different laminae are commonly of uneven grain size, which varies from 1 to 5 millimeters. In the hills west of Harper Dry Lake the gneiss is prominently laminated; in the Fremont Peak range it is somewhat more homogeneous, largely lacking in gneissoid banding, and grades into gneissoid quartz diorite.

The average composition of the gneiss is biotite-hornblende quartz diorite. The feldspars are opaque white and are mostly sodic plagioclase. The biotite flakes average 1 to 3 millimeters across and are mostly oriented parallel to the gneissoid banding, to give a planar foliation. The hornblende occurs as stubby prisms, likewise oriented with their long axes parallel to the gneissoid banding; in places, parallel orientation of the hornblende gives the rock a crude linear foliation. Secondary epidote commonly occurs as grains and thin veinlets on fracture surfaces. A sample of quartz diorite gneiss from 2 miles southeast of Fremont Peak is composed of quartz 23 percent; plagioclase feldspar (andesine) 52 percent; biotite 2 percent; hornblende 18 percent; opaque accessories 5 percent.

Minor masses of black schists composed mainly of biotite and hornblende occur in some of the northern exposures of gneiss, in the hills 4 to 5 miles west of Harper Dry Lake. The schists are well foliated, and form thin lenticular layers generally not over 50 feet thick. They grade into gneisses with the addition of quartz and feldspar.

Layers of white marble are intercalated in three of the exposures of the Waterman Gneissic Complex west of Harper Dry Lake. The marble layers are parallel to the foliation of the gneiss and range from a few inches to about 15 feet in thickness. The layers are lenticular and some lens out rapidly; others are traceable for over a mile. The marble is always white, massive to faintly bedded, and fine- to medium-textured, with grain sizes ranging from 1 to 4 millimeters. The marble is dolomitic and contains many impurities. Flakes of muscovite are scattered throughout the rock or concentrated along bedding planes. According to T. H. McCulloh (written communication, March 1952) a petrographic analysis of a sample from the hill in Sec. 14, T. 11 N., R. 5 W., near Lockhart Ranch, is composed of both calcite and dolomite, and contains magnesium silicates such as forsterite ($MgSiO_4$ 96 percent; $FeSiO_4$ 4 percent) with alterations to antigorite(?) or chlorite, diopside, and an unidentified rare silicate. Lime-silicate tactites are absent or rare in the Harper Valley exposures.

Gray quartzite containing biotite flakes occurs as rare lenses a few inches to a foot thick in the most northerly exposure of gneiss west of Harper Dry Lake.

Other rock types commonly associated with the gneiss west of Harper Dry Lake, but of later origin, are silicified mylonites(?) and pegmatites. The mylonites(?) occur as thin sheets in the gneisses, sometimes parallel to the foliation but more usually at a slight angle to it; the sheets range in thickness from an inch to several feet. The mylonites(?) are gray-brown, hard, dense siliceous rocks which break into thin plates that commonly have striated surfaces.

Small dikes of pegmatite are locally numerous in the gneisses exposed west of Harper Dry Lake. The dikes commonly are parallel to the gneissoid foliation; less often they are at an angle or even normal to it. They range in thickness from an inch to about a foot. The pegmatites are composed essentially of white feldspar, quartz, hornblende, and, locally, biotite. The grain size averages about half an inch and is rarely over an inch. These pegmatites are believed to be older than the granitic pegmatites associated with quartz monzonite, because the latter are of larger grain size and never contain hornblende.

Origin. The Waterman Gneissic Complex exposed west of Harper Valley appears to have been formed by metamorphism of sedimentary, and perhaps some pyroclastic and igneous rocks, under very high temperature and pressure at great depth. This is suggested by the uniformly medium-coarse texture of the series, and by the abundance of high-temperature minerals throughout. The white marbles were recrystallized from layers of dolomitic limestone; the quartzites from quartzose sandstones; and the biotite schists from shales.

The exact means of origin of the gneisses is controversial. They were formed either 1) by complete recrystallization of sedimentary or pyroclastic rocks such as shales, sandy shales, arkosic sandstones, tuffaceous shales, or tuffs, or possibly andesitic or basic volcanic rocks, in place, or 2) by lit-par-lit injection of a molten magma into a roof of folded or upturned metamorphic rocks, which crystallized into quartz diorite and diorite, or 3) in part by both means. The second hypothesis was suggested by Miller (1944, p. 80) and favored by Bowen (1954, p. 22). However, in the Fremont Peak quadrangle, as well as in many of the Hinkley Valley exposures, the first hypothesis is favored because of field relations as follows: 1) gneiss grades in all degrees into biotite schist and into gneissoid quartz diorite and diorite, 2) intercalations of marble, quartzite, and schist, together with their bedding or foliation planes, are almost always parallel with the foliation of the enclosing gneiss.

Probable Age. The Waterman Gneissic Complex is unfossiliferous, so that its age can be determined only within wide limits and inferred by comparison with similar rocks of which the upper age limits are known.

The Waterman Gneissic Complex is older than the quartz monzonite of Cretaceous age that intrudes it. The lower age limit is not known. Hershey (1902, p. 285–286) tentatively suggested a Precambrian, probably Archean, age to similar appearing schists and gneisses west-northwest of Barstow. Miller (1944, p. 78–79) expresses the same opinion, but suggests that his Hinkley Valley Complex may be as young as middle Paleozoic, and possibly (but unlikely) correlative with the type Oro Grande Series. The possibility that the Waterman Gneissic Complex may include rocks of Paleozoic age in a high grade stage of metamorphism cannot be ruled out. The writer is of the opinion, as pointed out by Miller (1944, p. 97–98) for his Hodge Complex, that these gneissic rocks are correlative with other similar gneissic rocks of the Mojave Desert region and the San Gabriel and San Bernardino Mountains, which are generally considered to be of Precambrian age; they are probably older than the nongneissic metamorphic rocks of known Paleozoic age of this region.

Bowen (1954, p. 22) assigned a late Paleozoic age to the Waterman gneiss by correlating it with the lower part of the Oro Grande Series, based on late Paleozoic gastropod and echinoid debris he reportedly found in an outcrop of dark greenish-gray limestone 2 miles northwest of Barstow that he (Bowen, 1954, p. 105) interpreted as being part of the Waterman Gneiss. Examination of this limestone by the writer reveals that it is totally unlike the white marbles within the Waterman Gneiss, and that it is separated from the underlying gneiss either by a major fault, as Bowen (1954, p. 23) indicates, or by a major unconformity. This dark-colored limestone is certainly not part of the Waterman Gneiss, but may be the basal(?) part of a Paleozoic or possibly a Tertiary formation.

Pre-Tertiary Intrusive Rocks

HORNBLENDE DIORITE

Distribution. In the eastern part of the Opal Mountain quadrangle hornblende diorite and minor gabbro and amphibolite crop out prominently in the William Plain area as three large exposures and as several small ones. Several small outcrops appear northwest and southwest of Superior Valley. Several exposures of these mafic rocks are in the southeastern part of the Fremont Peak range and in the hills west of Harper Dry Lake in the Fremont Peak quadrangle.

Topographic Expression. The hornblende diorite and related mafic rocks are strongly coherent and more resistant to weathering than the adjacent granitic rocks, and therefore protrude as hills. Outcrops of these mafic rocks invariably weather to irregular loose fragments and blocks as large as 5 feet across.

Photo 3. Exposure of hornblende diorite. View northwest from hills south of Coolgardie Camp; Black Mountain and Opal Mountain in distance.

Lithology. The hornblende diorite and associated mafic rocks are dark gray to nearly black and of inequigranular medium to very coarse texture. The rocks are nearly always massive with no discernible foliation. They are composed almost entirely of interlocking grains of white plagioclase feldspar (andesine to bytownite) and black hornblende, in proportions varying from 50 to 95 percent hornblende. The hornblende occurs in short stubby anhedral crystals, or as bladed crystals as long as three inches and as wide as half an inch. The hornblende crystals poikilitically enclose minute crystals of plagioclase, which also occurs as lathy anhedral crystals intergrown with the hornblende, or fills the spaces between the larger hornblende crystals. In places the rocks contain a little biotite, and the more basic gabbroic rocks contain small percentages of augite, hypersthene, phlogopite, and olivine. Accessory minerals are magnetite, sphene, and apatite. Secondary alteration minerals are epidote, chlorite, clinozoisite, sphene, iron oxides, and calcite. In the vicinity of Coolgardie Camp the gabbroic rock locally contains nodules as large as 5 inches across of nonmagnetic iron oxide.

Relationships to Other Rocks. The hornblende diorite occurs as isolated bodies, usually in quartz monzonite; a few small ones are adjacent to quartz dio-

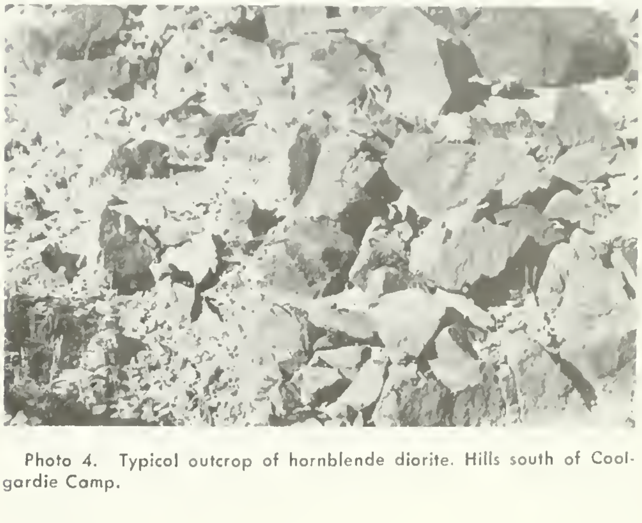


Photo 4. Typical outcrop of hornblende diorite. Hills south of Coolgardie Camp.

rite; none occur in the Waterman Gneissic Complex. The relationships of the hornblende diorite to the enclosing granitic rocks are not clear. The hornblende diorite masses are possibly intrusive into the granitic rocks. However, in the northernmost of the three large exposures of hornblende diorite in the Williams Plain area of eastern Opal Mountain quadrangle, the contact of the hornblende diorite and enclosing quartz monzonite dips inward under the hornblende diorite from all sides, in places at low angles. This indicates the hornblende diorite was intruded from below by the quartz monzonite—that is, the hornblende diorite is a pendant in the quartz monzonite. A similar situation is suggested in the large central exposure of hornblende diorite to the south, where the contacts also dip under the hornblende diorite. In the southern large mass of hornblende diorite near Coolgardie Camp, the contacts with quartz monzonite are near vertical, but in places dip steeply under the hornblende diorite. This mass grades northeastward into quartz diorite. All the masses of hornblende diorite in the Williams Plain area are within quartz monzonite and nearly all are elongated in an east-northeast direction. Contacts with the quartz monzonite are generally sharp and there are no apparent textural gradations in either rock type near their contacts.

The large mass of hornblende diorite in the southeastern Fremont Peak range occurs in quartz monzonite midway between a large exposure of quartz diorite and one of quartz diorite gneiss; the mass is elongated northeastward parallel to the contacts, which are vertical or steep.

Northwest of Superior Valley, hornblende diorite occurs as isolated circular bodies in quartz monzonite and is associated with quartz diorite.

It is concluded that the hornblende diorite is either intrusive into the quartz monzonite or is intruded by the quartz monzonite. The latter seems more likely, at least in the Williams Plain area where the contacts of the two rock types dip under the hornblende diorite. If so, the hornblende diorite occurs as isolated pendants within the quartz monzonite.

Origin. The hornblende diorite is of either magmatic or extreme metamorphic origin. The igneous origin is suggested by its interlocking grain texture and lack of planar or linear structure. However, the north-eastward elongation of the hornblende diorite masses and the inward dip of their contacts with the adjacent quartz monzonite in which they are engulfed suggests that the hornblende diorite may have been formed by complete recrystallization of a metamorphic rock, such as gneiss or ferromagnesian-rich schist, under conditions of extremely high temperature. The high concentration of hornblende at the expense of potassium feldspar and quartz may have resulted from settling or segregation of the heavy ferromagnesian content of the semimolten roof rock into the roots of the pendants during the batholithic invasion of the quartz monzonite magma.

Age. The hornblende diorite is probably about the same age as the quartz diorite, that is, probably younger than the Precambrian(?) Waterman Gneissic Complex, but older than the Cretaceous quartz monzonite that probably intrudes it. If it was formed by recrystallization of a pre-existing rock when it was invaded by the quartz monzonite magma, it would be about the same age as the quartz monzonite.

QUARTZ DIORITE

Distribution. Quartz diorite crops out adjacent to the north Lockhart fault west of Harper Dry Lake and in the southeastern part of the Fremont Peak range. Other exposures occur in the extreme northern part of the mapped area and extend north of it; still others are near the eastern border of the Opal Mountain quadrangle and extend east of it.

Topographic Expression. The quartz diorite is weakly coherent and weathers readily by mechanical separation of grains, with the abundant biotite flakes acting as separation planes. This rock thereby weathers to low relief as does the adjacent quartz monzonite.

Structure and Relationships to Other Rocks. In the exposure of quartz diorite adjacent to the north Lockhart fault west of Harper Valley, the rock is faintly gneissoid but is of homogeneous texture and is intruded on the west by quartz monzonite. The indistinct planar foliation trends northwest and is vertical. A small sliver of ferruginous limestone occurs in this mass adjacent to the fault. At the east end of this exposure the quartz diorite contains a small mass of hornblende diorite.

The large exposure of quartz diorite in the low southeastern portion of the Fremont Peak range is similar to the exposure just described. The weak planar foliation of this rock is vertical with a northeasterly trend. The quartz diorite is bounded on both sides by quartz monzonite that is instrusive into it. In the exposures north of the Gravel Hills and all those within the Opal Mountain quadrangle, the quartz diorite is generally massive; in a few places it is weakly gneissoid. The quartz diorite of all these exposures occurs as irregular masses or pendants within quartz monzonite, in most places with sharp contacts.

Lithology. The quartz diorite is dark gray, medium-grained, and equigranular, with grains ranging from 2 to 5 millimeters. It is composed essentially of plagioclase (andesine), quartz, biotite, and hornblende in variable proportions, but generally in that order of decreasing abundance. In places a little orthoclase is present so that the rock varies to granodiorite. In others there is little or no quartz so that it varies to diorite. Accessory minerals include epidote, sphene, magnetite, ilmenite, zircon, and apatite. The feldspars and quartz occur as translucent equant anhedral grains; the biotite as numerous small flakes; and the hornblende as short stubby prisms. The rock is homogeneous, but gneissoid foliation results locally from parallel orientation of the biotite flakes and hornblende prisms. Secondary fine-grained epidote is commonly present as thin coatings on fracture surfaces.

Age. The quartz diorite is younger than the Waterman Gneissic Complex of Precambrian(?) age from which it may have been formed, and older than the quartz monzonite of Cretaceous age that intrudes it.

It was formed during one of these periods, or during the long interval between them.

GRANODIORITE

Granodiorite crops out in the Waterman Hills, south of the Mud Hills in the extreme southeastern part of the Opal Mountain quadrangle. The major portion of this exposure lies south of the quadrangle, where it was described as biotite granodiorite by Bowen (1954, p. 64–65).

The granodiorite weathers to low relief. It is a light gray, medium-textured equigranular rock. It is generally massive but locally has faint linear foliation that in places dips steeply southwest. The rock is composed of quartz 20–26 percent; potash feldspar (orthoclase) 10–14 percent; plagioclase feldspar (oligoclase) 47–60 percent; biotite 3–8 percent; hornblende, 0–1 percent. Minor accessory minerals are magnetite and apatite. Minor alteration products are chlorite, epidote, sphene, and rutile.

Mapping by the writer in the Waterman Hills 2 miles south of the border of the Opal Mountain quadrangle indicates that the granodiorite grades southeastward into a more basic, gneissoid rock, probably gneissoid quartz diorite, then into quartz diorite gneiss. This indicates that the granodiorite probably formed at least in part by recrystallization or "granitization" of gneiss.

QUARTZ MONZONITE

Distribution. The quartz monzonite is the most widespread of the pre-Tertiary crystalline rocks within the mapped area, and is exposed extensively in the western and extreme northern and eastern parts. Smaller exposures occur near Opal Mountain and southwest of the Mud Hills.

Topographic Expression. In the arid desert climate the normal biotite-bearing quartz monzonite disintegrates mechanically into its constituent grains to form coarse residual granitic sand (grüs). Exposures of this rock therefore weather to low, subdued topography. In the Fremont Peak range, a coherent fine-grained phase of quartz monzonite with no biotite is more resistant to weathering and forms steep, rugged topography. This rock fractures along joints to form large irregular blocks.

Field Relations. The quartz monzonite exposed within the mapped area is part of an extensive, generally uniform batholithic mass that apparently underlies most of the western Mojave Desert, both exposed at the surface and concealed beneath Cenozoic formations. The relations of the quartz monzonite with the other plutonic rocks have already been described. Its boundaries with the hornblende diorite are sharp, but those with the quartz diorite are less distinct and commonly gradational. In some places the quartz monzonite sends small aplitic apophyses a few inches or feet wide into both rocks.

The quartz monzonite intrudes the Waterman Gneissic Complex, in most places with sharp and discordant contacts, with some apophyses projecting into the gneiss. However, in exposures west and northwest of Fremont Peak, the contact is gradational, with as much as several hundred feet of transitional rock that may be granodiorite containing faint relict foliation accordant with that of the adjacent quartz diorite gneiss. At Fremont Peak and southeastward for 3 miles a fine-grained facies of the quartz monzonite is in sharp contact with the gneiss, and the contact is accordant with the foliation of the gneiss. This mass

Photo 5. Fremont Peak, viewed from the east, showing rugged topography formed by resistant fine-grained leuco-quartz monzonite.

Photo 6. Outcrops of quartz monzonite west of Harper Dry Lake.

Photo 7. Typical outcrop of quartz monzonite cut by a small pegmatite dike. North of Mud Hills at eastern border of Opal Mountain quadrangle.

of fine-grained quartz monzonite appears to be in part a large sill-like body intrusive into the gneiss. Within the gneiss about a quarter of a mile south of this contact is a small but conspicuous sill of this same facies of quartz monzonite that is accordant with the foliation of the gneiss.

Lithology. Most of the quartz monzonite within the mapped area is gray-white and massive, with no visible foliation. It is medium- to coarse-grained, and equigranular, with the grain size ranging from 1 to 4 millimeters. This rock is composed essentially of quartz, alkali feldspar (orthoclase and microcline), and plagioclase (oligoclase, rarely andesine). These are generally in about equal proportions, although the percentages of the feldspars vary locally. The quartz is clear and glassy; the feldspars opaque white to cream-white. Biotite, in amounts up to 12 percent, occurs commonly as scattered euhedral tablets 2 to 4 millimeters across. In places the rock contains a little muscovite and hornblende. Magnetite, sphene, apatite, and zircon occur as very small grains, and together rarely exceed 1 percent of the rock.

At Fremont Peak and vicinity is a leucoquartz monzonite. This rock differs from the normal quartz monzonite in its generally finer grained texture and whiter color, biotite being absent. Near Fremont Peak the rock approaches aplite, with an average grain size between 1 and 2 millimeters. This rock is composed of quartz 30 percent; potassium feldspar 40 percent; plagioclase (oligoclase) 30 percent; muscovite and biotite, less than 0.5 percent. This leucoquartz monzonite grades southward into normal quartz monzonite.

The quartz monzonite exposed south of Opal Mountain differs from the normal variety in that it is coarser grained. The quartz and feldspar grains range from 3 to 8 millimeters, and the rock is practically devoid of biotite.

Photo 8. Typical exposure of quartz monzonite, overlain by Jockhammer and Pickhandle Formations (exposed at upper left). North of Mud Hills at eastern border of Opal Mountain quadrangle.

In the low hills at the extreme southeast end of the Fremont Peak range the quartz monzonite is contaminated with numerous small hybrid masses of incompletely assimilated mafic rocks such as quartz diorite and hornblende diorite. Within this complex, irregular mylonitic crushed zones are locally numerous.

Age. The quartz monzonite is younger than the Precambrian(?) Waterman Gneissic Complex, as well as the pre-Cretaceous(?) quartz diorite and hornblende diorite it intrudes; it is older than all the Tertiary sedimentary and pyroclastic rocks, which lie uncomformably on it. It is older than the pegmatite and aplite dikes which cut it and which are of probable early Cretaceous age, and it is older than the quartz latite dikes of probable Cretaceous age.

Samples of quartz monzonite from several localities in the western Mojave Desert, including one from the nearby Lane Mountain area east of Williams Plain, have been determined by means of lead alpha content of zircon to range from 93 to 122 million years old, or Cretaceous age (according to the U.S. Geological Survey, W. G. Schlecht, written communication, 1957).

PEGMATITE AND APLITE

Distribution and Field Relations. In the vicinity of hill 3824 in northeastern Fremont Peak quadrangle, pegmatite occurs as a swarm of dikes intrusive into both quartz monzonite and quartz diorite. Pegmatite dikes make up more than 50 percent of the granitic rock of this hill, and many merge into a nearly solid mass of pegmatite. Within a radius of about 2 miles of this hill the dikes become less numerous and scattered. They are oriented at random and many join or intersect, although in hill 3824 most of the dikes trend northwest. In the foothill areas east of hill 3824, north of upper Black Canyon, the quartz diorite is intruded by other numerous pegmatite dikes that trend mostly east-west. In both these areas the pegmatite dikes are vertical or steeply inclined, and range in width from less than an inch to as much as 10 feet.

West of Harper Valley, the most southerly exposure of Waterman Gneissic Complex is cut by numerous dikes of pegmatite that appear to be offshoots from the quartz monzonite to the west.

North of the western Mud Hills, a series of parallel vertical east-trending aplite dikes intrude quartz monzonite; no pegmatite is present. The dikes vary from a few inches to 10 feet in width, averaging about 3 feet. In the area south of the Mud Hills the granodiorite is cut by several vertical dikes of aplite that trend northwesterly.

The pegmatite and aplite dike rocks are strongly coherent and much more resistant to weathering and erosion than the enclosing quartz monzonite and quartz diorite, so that they protrude as little ridges.

Lithology. The pegmatites are very coarse-textured white rocks composed almost entirely of quartz and feldspars in interlocking anhedral grains as large as an inch across. Textures are highly variable; many dikes have zonal textural banding, with the internal portion composed of coarse pegmatite that grades outward through medium-grained graphic pegmatite to micropegmatite or even aplite at the margin.

The pegmatites are about one-third quartz and two-thirds feldspar. The quartz is translucent and glassy. The feldspars, which are opaque-white to cream-white, and are composed of potassium feldspar (orthoclase and microcline), and plagioclase feldspar (albite-oligoclase) in varying proportions. The only accessory minerals are a little muscovite, biotite, and (rarely) black tourmaline, which together make up less than 1 percent of the rock.

The aplites (or micropegmatites) are massive, fine-textured, nearly white rocks with an average grain size of about 1 millimeter. They are composed of quartz and feldspar in about the same proportions as in the pegmatites. The only accessory mineral is a little muscovite.

Age. The pegmatite and aplite are younger than the granitic rocks, including the Cretaceous quartz monzonite, that they cut. However, they are probably only very slightly younger than the quartz monzonite because they must have formed in or intruded it at depth while it was still very hot. They intrude no rocks younger than the quartz monzonite, but occur as clasts in all Tertiary sedimentary formations so they must be older than the oldest Tertiary (Miocene) sediments exposed. From the above relationships it may be concluded that the pegmatite and aplite rocks are of late Cretaceous or early Tertiary age.

QUARTZ LATITE PORPHYRY

Distribution. Dikes of rhyolitic porphyry with the average composition of quartz latite are widely distributed throughout the Fremont Peak range, especially in the northern portion. Scattered dikes also occur in the low hills west of Harper Valley.

Topographic Expression. The quartz latite is strongly coherent, hence highly resistant to weathering and erosion. Dikes of this rock protrude prominently from the less resistant granitic and metamorphic rocks as little ridges. The rock weathers by fracturing along joints into angular blocks and fragments.

Relationships to Other Rocks. The quartz latite occurs as vertical or steeply dipping planar sheets or dikes less than a foot to as much as 70 feet thick. Many of them have parallel walls and are traceable for a mile or more; others are lenticular and pinch out at both ends within short distances. Several occur as lenticular bodies as much as 1,000 feet thick, such as the one 2 miles southeast of Fremont Peak. The dikes cut sharply through pre-Tertiary granitic and metamorphic rocks alike, and the position and trend of the dikes are completely independent of the contacts and internal structures of these rocks. In the northern Fremont Peak range the quartz latite forms a system of numerous, parallel, east-trending dikes dipping steeply north. In the southeastern portion of the range it occurs as scattered near-vertical dikes trending east to northeast with some merging or intersecting. Small dikes in the low hills west of Harper Valley are vertical and trend east to southeast.

Lithology. The quartz latite is very hard and ranges in color from nearly white through tan and pale-gray to medium-gray. Joint surfaces are commonly coated brown by iron oxides. The rock is nearly always massive, but rarely has flow-banding. The texture varies considerably: the smaller dikes and margins of the larger dikes are dense, felsitic; the internal portions of the larger dikes are porphyritic; and the largest bodies are locally granophyric.

The felsitic type, and the groundmass of the porphyritic type, are very fine-grained, anisotropic, with an average refractive index of 1.54. The rock is a fine-grained mosaic of quartz and feldspar, with specks of hematite, chlorite, rutile, and indeterminate opaque minerals. Some of the felsitic rock is severely sericitized, commonly with crude foliation parallel to the walls of the dike. In the porphyritic type, the phenocrysts are euhedral to subhedral, and are composed of clear to opaque-white potassium feldspar (sanidine?), or white plagioclase feldspar (oligoclase), or both; small tablets of biotite; and rare small prisms of hornblende. The phenocrysts constitute as much as 25 percent of the rock.

Photo 9. Typical outcrop of quartz latite dike (ql) in gneiss (gn), 3 miles southeast of Fremont Peak.

Origin. The quartz latite was emplaced as sheets of magma in a well-defined system of parallel joints or faults in the pre-Tertiary crystalline granitic and metamorphic rocks. These openings apparently formed long after the granitic rocks were solidified, because the sheets of quartz latite pass through the granitic and metamorphic rocks alike without regard to their contacts or internal structures. The felsitic texture of the quartz latite indicates it to have crystallized rapidly while the temperature of the host rock was low.

Age. The quartz latite is younger than the Cretaceous quartz monzonite that it intrudes, and older than the late, middle, and upper Miocene Barstow Formation in which it occurs abundantly as clasts in the Gravel Hills. These relationships indicate that the quartz latite is either Cretaceous or early Tertiary in age.

BASALTIC PORPHYRY

Gray-black dikes of basaltic or andesitic porphyry are associated with the rhyolitic dikes in the Fremont Peak range and are presumably of the same Cretaceous or early Tertiary age. They occur in the extreme northern part of the range, in the low portion about 4 miles south of Fremont Peak, and in the extreme southeast portion near Darton Spring.

The basaltic dikes, as much as 10 feet wide, cut quartz monzonite and quartz diorite gneiss. They trend generally east-west, parallel to associated dikes of quartz latite, and are nearly vertical.

The rock of the basaltic dikes is porphyritic with an aphanitic to fine-grained diabasic, black groundmass containing rectangular phenocrysts of white plagioclase as much as 5 millimeters in longest dimension. The phenocrysts make up as much as 20 percent of the rock mass.

Tertiary Rocks

JACKHAMMER FORMATION

Areal Distribution. The basal unit of the Tertiary sequence exposed in the Calico Mountains was named the Jackhammer Formation by McCulloh[*] for exposures in the Jackhammer Gap area of the northwestern Calico Mountains. At this type locality, in the Lane Mountain quadrangle, the formation consists of about 650 feet of arkosic sandstone, conglomerate, tuff, and basalt, in ascending order.

Since McCulloh's work has not been published, he has kindly consented to the publication here of extracts from his thesis to provide descriptions of the type localities of some of his newly defined formational units. His description of the type section of the Jackhammer follows:

"The Jackhammer Formation, where it is not missing due to non-deposition or post-depositional erosion, is the lowermost formation of the Tertiary section. The basal beds rest unconformably upon a surface of relatively low relief cut across various crystalline rocks of the basement complex. The best exposures and thickest development of the formation are in the vicinity of Jackhammer Gap, between one mile east and one mile west of the Barstow-Camp Irwin Road. Sporadic outcrops are found farther to the southeast to a point in Sec. 25 [T. 11 N., R. 1 E.] the southern edge of the [Lane Mountain quadrangle] area. The formation is represented also at the base of the Tertiary section west of the Randsburg-Barstow Road near the western edge of the area.

"Stratigraphy

"The type section of the formation is located west of the Barstow-Camp Irwin Road in Secs. 17 and 20, T. 11 N., R. 1 E., approximately 2000 feet NNE of Jackhammer Gap in the northwestern Calico Mountains. It includes all of the rocks between the base of the lowermost prominent reddish-brown dacite mudflow breccia and the unconformity at the base of the Tertiary section. The included stratigraphic units, from top to base, are given below.

Thickness (feet)	*Character*
345	Dacite tuff, tuff breccia, and tuffaceous sandstone; green-gray, light gray, and white, poorly stratified to well stratified hornblende-biotite dacite tuff and tuff breccia; some interbedded brown tuffaceous sandstone. Angular fragments of light gray, pumiceous dacite porphyry several inches in diameter are abundant in some beds, and subangular pebbles of hornfels and fine-grained quartzite are important constituents of a few beds.
15	Tuff; white to light gray, well-stratified, thinly-bedded to massive, and fine-grained.
200	Basalt; black to reddish-black massive amygdaloidal olivine basalt.
150	Conglomeratic arkose and tuff; principally arkose and conglomeratic arkose; pink, poorly- to well-stratified, poorly sorted, medium- to coarse-grained. Smoothly rounded cobbles and pebbles of resistant rock types of the basement complex are characteristic.

"Although the units exposed in the type section are characteristic of the formation, there are considerable lateral variations in thickness and lithology.

"Age

"A complete absence of fossils leaves the age of the Jackhammer Formation in doubt. The possibilities are, however, practically limited to early or middle Tertiary.

"The formation rests with profound nonconformity upon Mesozoic (?) plutonic and Paleozoic metamorphic rocks. The probability that it is Cretaceous is essentially nil judging by the regional geology, and the formation can be no younger than upper Miocene, since rocks of that age overlie it.

"Nothing more is known of the age. However, the speculation is offered, that, since older Tertiary rocks are not known in the Mojave Desert region between the Garlock and San Andreas faults, while Miocene and younger rocks are widespread, a tentative questionable Miocene age assignment is favored."

Along strike west of Jackhammer Gap the Jackhammer Formation is concealed beneath Quaternary alluvium, but reappaears about 100 feet thick in the Mud Hills west of the Barstow-Goldstone road on the north flank of the Barstow syncline. The Jackhammer Formation strikes westward into the Mud Hills fault near the eastern border of the Opal Mountain quadrangle, then is offset to the northwest, where it is traceable for about a mile west to Owl Canyon. West of Owl Canyon, it crops out only locally under Quaternary alluvium for another 2 miles.

Topographic Expression. The Jackhammer Formation is less resistant to erosion than the underlying quartz monzonite and overlying Pickhandle Formation, and so is exposed primarily in small valleys and saddles aligned between exposures of these more resistant rocks. The tuff bed forms prominent white exposures, but the overlying basalt flow readily weathers to a deep red soil.

Lithology. In the Mud Hills the Jackhammer Formation is best exposed at the head of Owl Canyon on the north flank of the Barstow syncline, where the formation is about 100 feet thick. The lower and major portion, ranging up to about 70 feet thick, consists of pinkish-gray, medium- to coarse-grained arkosic sandstone containing scattered rounded pebbles and cobbles of quartz monzonite and quartzite. The upper portion of the Jackhammer Formation consists of a few feet of soft white bentonite overlain by 0–3 feet of white, bedded, fine- to medium-grained arkosic tuff; then 0–30 feet of black amygdaloidal basalt. The bentonite and tuff both lens out westward from Owl Canyon, and also eastward at the border of the quadrangle. The basalt flow lenses out eastward in Owl Canyon, and is exposed in several isolated outcrops for 2½ miles westward of Owl Canyon; beyond that, it is weathered to a deep reddish soil. At the eastern border of the quadrangle the Jackhammer Formation consists of a lens of hard, light-gray, sandy to pebbly limestone about 15 feet thick, traceable for about 1,000 feet.

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[*] McCulloh, T. H., Geology of the southern half of the Lane Mountain quadrangle, California: PhD. thesis, Univ. of Calif., at Los Angeles, 1952, unpublished.

Stratigraphic Relations. The Jackhammer Formation rests on the eroded and weathered surface of quartz monzonite which prior to deposition was weathered brick-red as much as 25 feet below its former surface. The Jackhammer Formation is conformably overlain by tuffaceous granitic cobble conglomerates of the Pickhandle Formation. The tuff and basalt flow are arbitrarily placed in the Jackhammer Formation, as was done in the type locality at Jackhammer Pass by McCulloh.

Probable Age. No fossils have been found in the Jackhammer Formation, so that its age within the Tertiary is uncertain. Since it lies conformably below the Pickhandle Formation of supposed middle Miocene age, it is probably only slightly older than that formation, so is presumably middle Miocene or older.

PICKHANDLE FORMATION

Areal Distribution. The Pickhandle Formation was mapped and named by McCulloh * for a sequence of pyroclastic rocks exposed in the Pickhandle Pass area of the northwestern Calico Mountains of Lane Mountain quadrangle. In this type area the Pickhandle Formation, of supposed middle or possibly lower Miocene age, is about 4,900 feet thick. It rests conformably on the Jackhammer Formation and is unconformably overlain by the Barstow Formation.

McCulloh describes the type area as follows:

"The Pickhandle Formation is named for Pickhandle Pass in the western Calico Mountains. The formation attains its greatest thickness about one half mile west and northwest of the Pass. The base of the formation is there designated to be the base of the lowermost red-brown dacite mudflow breccia exposed in Jackhammer Gap, and the top is designated to be the base of the predominantly thinly stratified tuffaceous and calcareous beds which dip gently toward the south in the northern part of Sec. 31, T. 11 N., R. 1 E.

"Stratigraphy

"The Pickhandle Formation is the thickest, and lithologically most diversified, Tertiary formation of the area. It crops out in a discontinuous northwesterly- to westerly-trending belt which extends across the entire southwestern corner of the area. The most completely exposed, and structurally least complicated, section is found along the western edge of the area. There, the following members, from top to base, have been differentiated. The thicknesses given are obtained graphically by construction from the geologic map. For comparison, a columnar section of all the Tertiary formations exposed in the northern limb of the Barstow syncline, just west of this [Lane Mountain quadrangle] area, measured by C. Durrell and A. C. Dailey . . . (Durrell, 1953, plate 4) is cited.

Thickness (feet)	*Lithology*
125	Granitic conglomerate: dark green to brown, well-cemented, massive, ill-sorted, coarse, sandy cobble conglomerate.
100	Hornblende andesite tuff breccia: light brown to pink, poorly and massively stratified, coarse.
350	Quartz monzonite breccia: brown, massive, extremely coarse; thin discontinuous zone of white rhyolite breccia near middle.
225	Tuff, sandstone, and siltstone: 6-inch layer of brick-red sandy siltstone resting upon 200 feet of light gray, incompetent, poorly stratified sandy tuff, which rests upon red-brown, thinly bedded, soft mudstone and claystone.
300	Quartz monzonite breccia: brown, massive, extremely coarse; water-worn material at base and top; massive, shattered quartz monzonite for the most part; thin zone of white rhyolite breccia near the base.
1400	Dacite tuff breccia: upper half light pink to tan; lower half light green to yellow; poorly stratified, massive, coarse.
500±	Tuff, tuff breccia, and sandstone: zone of extremely variable lithology.

Total thickness = 3050 ± feet.

"Age

"The Pickhandle Formation has yielded no fossils. It is overlain by the upper Miocene Barstow Formation, and it rests upon the Jackhammer Formation, the age of which is unknown. The same considerations which led to the questionable dating of the Jackhammer Formation as Miocene (?) cause the writer to assign the same tentative age to the Pickhandle Formation."

From the Pickhandle Pass area of the Calico Mountains the Pickhandle Formation strikes westerly into Opal Mountain quadrangle through the Mud Hills where it is prominently exposed on the north flank of the Barstow syncline, as mentioned by McCulloh. To the north there are several small isolated outcrops apout 4 miles northwest of Coolgardie Camp. The Pickhandle Formation is also well exposed where it is associated with rhyolitic volcanic rocks in the Opal Mountain-Black Canyon area, and in the crestal portions of the Gravel Hills, to the west.

Photo 10. Large rhyolitic plug of Opal Mountain Volcanics (Tri) intrusive into tuff (Tpt) of Pickhandle Formation, 2 miles east of Fremont Peak.

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* McCulloh, T. H., Geology of the southern half of the Lane Mountain quadrangle, California: PhD. thesis, Univ. of Calif., at Los Angeles, 1952, unpublished.

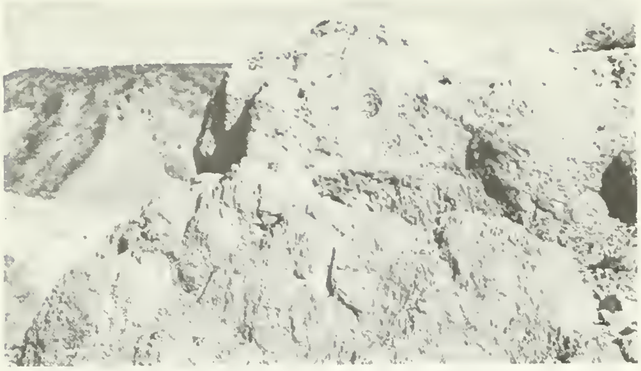

Photo 11. Outcrop of perlite of Opal Mountain Volcanics near Hicks perlite quarry, Black Canyon.

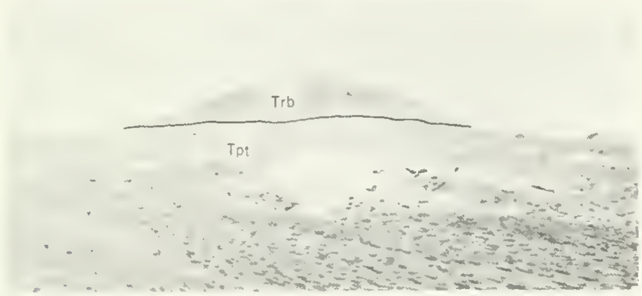

Photo 12. Exposure of pumiceous tuff (Tpt) of Pickhandle Formation overlain by rhyolitic flow breccia (Trb) of Opal Mountain Volcanics. Williams pumicite quarry.

Lithology. The Pickhandle Formation consists predominantly of pyroclastic sediments, mainly light-colored, rhyolitic, lithic, and lapilli tuffs. Other rock types locally present in this formation, in the form of lenses of limited areal extent, are volcanic agglomerates, granitic breccias, conglomerates, sandstones, clays, and limestones.

Rhyolitic lavas are widely associated with the pyroclastic rocks of the Pickhandle Formation. Some are intrusive, others extrusive. They are widespread in the Opal Mountain and Gravel Hills areas, and are separately mapped and described as the Opal Mountain Volcanics. In the Mud Hills, andesite occurs in one exposure of the Pickhandle Formation, and near Opal Mountain this formation contains at least one basalt flow.

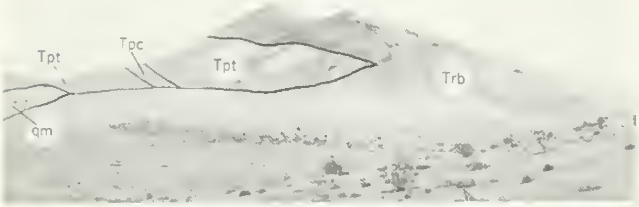

Photo 13. Opal Mountain, viewed from the northwest, showing the following rock units: quartz monzonite (qm); tuff (Tpt) and granitic conglomerate (Tpc) of the Pickhandle Formation; and rhyolitic flow breccia (Trb) of Opal Mountain Volcanics.

The white or light-colored lithic and lapilli-tuffs that compose the major part of the Pickhandle Formation are fine-grained, ill-sorted tuff and sandy tuff. Both contain grains of quartz and feldspar, flakes of biotite, angular lithic fragments of volcanic rocks, granitic rocks, reworked tuff, and subrounded lapilli fragments of devitrified pumice or pumiceous perlite. Most of the lithic fragments are Tertiary volcanic rocks, mainly brown porphyritic andesite or latite, and brown and red-to-pink, flow-banded rhyolitic rocks. Some gray perlite is also present. In some layers many of the fragments consist of dense white material that is either devitrified perlite or reworked tuff. The granite fragments are mostly biotite quartz monzonite. The lithic fragments are angular to subrounded and are usually less than half an inch in size. Locally some fragments, especially those of quartz monzonite, are of cobble or boulder size. The lapilli fragments of pumice or pumiceous perlite are mostly of pea-size. In most places these are devitrified to a soft white material, except at the Williams pumicite quarry, where in some layers they are quite fresh.

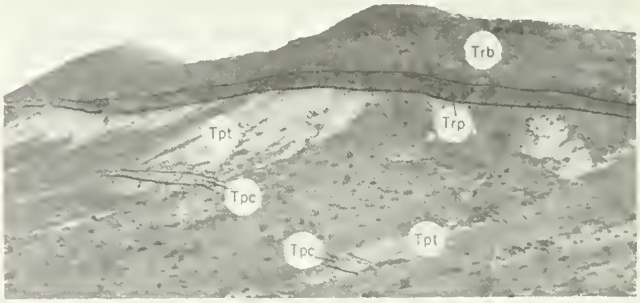

Photo 14. Opal Mountain, viewed from the north. Rhyolitic flow breccia (Trb) and perlite (Trp) of Ord Mountain volcanic formation overlying tuff breccia (Tpt) which contains layer of granitic boulder-cobble conglomerate (Tpc).

Facies of pure to sandy, fine-grained white tuffs with little or no lithic or lapilli fragments occur locally but are not common. These are confined to the upper part of the Pickhandle Formation in the Opal Mountain-Black Canyon area. Interbedded are clays and occasional limestones that must have been deposited in a lake.

The fragmental tuffs grade into tuff-breccias and agglomerates with increase in the size and abundance of the angular volcanic rock-fragments. In some breccias the angular fragments average as much as a foot across.

The tuffs grade into tuffaceous arkosic sandstones and conglomerates. Conglomerates are abundant in the lower part of the Pickhandle Formation on the north flank of the Barstow syncline, where they consist largely of rounded cobbles and boulders of granitic detritus up to a foot in diameter. In some layers the fragments are of dark-gray andesite porphyry. Small lentils of conglomerate of granitic boulders occur in the lower part of the Pickhandle tuff in the Black Canyon-Opal Mountain area. In the Mud Hills area

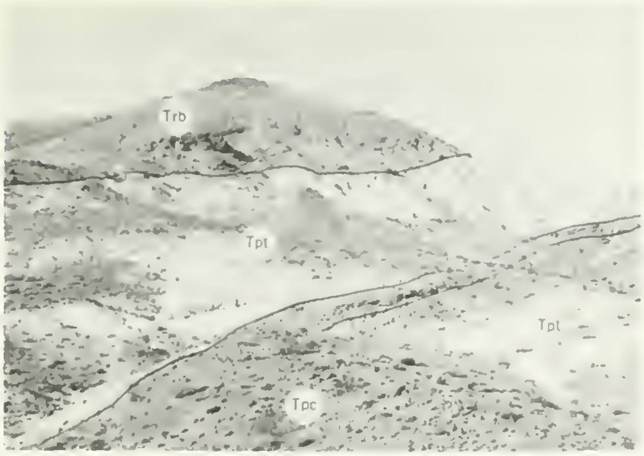

Photo 15. View north from Opal Mountain, showing rhyolitic flow breccia (Trb) overlying tuff breccia (Tpt) which contains layer of granitic boulder-cobble conglomerate (Tpc).

the upper part of the Pickhandle Formation contains huge lentils of coarse monolithic granitic breccias, which appear to be landslide masses of granitic rock within the breccias and the white, fine-grained rhyolite.

In the mapped area, chemically deposited sediments of lacustrine origin are comparatively rare in the Pickhandle Formation. The only ones exposed are in the upper part of the formation southwest of Opal Mountain, where fine-grained tuffaceous strata contain several thin layers of impure ferruginous limestone and chert-jasper.

Pickhandle Formation in the Mud Hills. The Pickhandle Formation is superbly exposed on the north flank of the Barstow syncline in the Mud Hills where it is about 2,800 feet thick. It may be separated into three fairly distinct parts: lower part, about 650 feet thick, mixture of gray cobble conglomerate and lithic-tuff; middle part, about 1,150 feet thick, light-colored, lithic-lapilli sandy tuff and lenses of tuff-breccia; and upper part, about 1,000 feet thick, composed of huge lenses of granitic breccia and some of white rhyolitic breccia lensing eastward into tuff. The stratigraphic sequence varies along strike in the Mud Hills, but several characteristic sequences are given below.

Pickhandle Formation at Owl Canyon, Mud Hills
(sec. 18, T. 11 N., R. 1 W.)

	Thickness (feet)
Unconformably overlain by basal conglomerate of Barstow Formation.	
Upper Part	
Granitic breccia, gray, unbedded	450
Rhyolitic felsite breccia, white, unbedded	0–50
Granitic breccia, gray to reddish, unbedded	500
Middle Part	
Lithic tuff, greenish-white, massive to crudely bedded, with andesitic and rhyolitic rock fragments	350
Lithic tuff, as above, but white to tan, includes some greenish-brown andesitic tuff-breccia both west and east of canyon	800
Lower Part	
Sandstone, greenish to reddish-gray, bedded, arkosic to tuffaceous, fine-grained to conglomeratic, with granitic pebbles and cobbles, replaced west of canyon by 0–150 feet of granitic breccia similar to those above	0–150
Conglomerate, dark bluish to greenish-gray, with cobbles and boulders of quartz monzonite, and to the west composed mainly of cobbles of andesitic porphyry in tuffaceous sandy matrix	250
Conglomerate, gray, with cobbles and boulders of quartz monzonite in tuffaceous sandstone matrix	250
Total thickness	2,800
Underlain by basalt flow of Jackhammer Formation.	

Pickhandle Formation exposed at Opal Mountain and southwesterly toward Black Mountain (secs. 7, 8, 18, 19, T. 32 S., R. 45 E., M.D.M.)

	Thickness (feet)
Unconformably overlain by Black Mountain Basalt.	
Tuff: White, stratified, moderately indurated, medium- to fine-grained; minor interbeds of lapilli tuff; and thin interbeds as much as a foot thick of light gray tuffaceous clay; about 200 feet above base is a stratum as much as a foot thick of gray cherty limestone	300
Limestone or dolomite: In beds as much as 2 feet thick, gray to brown, in part altered to ferruginous rust-colored chert and jasper; forms prominent strike-ridge	10
Basalt: Brownish-black, vesicular, with fine-grained diabasic texture; with vesicles ⅛ to ½ inch diameter, some filled with chalcedony or calcite; rock weathers soft	250
Lithic tuff: White, stratified, composed of small fragments of rhyolitic rock, reworked tuff, and lapilli of devitrified pumice in fine-grained tuff matrix	300
Rhyolitic flow breccia (of Opal Mountain Volcanics) Reddish-brown, lower 20 feet composed of gray perlite; forms Opal Mountain	300±
Lithic tuff: Same lithology as that above	200
Boulder conglomerate: Subrounded granitic boulders up to 2 feet diameter in arkosic sandy matrix	20
Lithic tuff: Same lithology as that above; rests unconformably on quartz monzonite weathered red	200
Total exposed thickness of Pickhandle Formation, (exclusive of rhyolitic flow breccia)	1,280

Pickhandle Formation exposed in central Gravel Hills
(secs. 25, 26, 36, T. 31 S., R. 43 E.)

	Thickness (feet)
Overlain by sandstone and conglomerate of Barstow Formation	
Rhyolitic flow breccia: dark red, locally green	0–200
Lithic and lapilli tuff: white, stratified moderately indurated, composed of small brown rhyolitic fragments and pea-size lapilli of white devitrified pumiceous obsidian; basal part soft, bentonitic, with lentils up to 30 feet thick of conglomerate of granitic and dioritic cobbles	500±
Rhyolitic rock (of Opal Mountain Volcanics): large central mass of red rhyolitic breccia; either a large extrusive volcanic pile, or a large sill-like pod; lenses out to east and west	0–1000?
Breccia: light gray, composed of angular rubble of gray pumiceous obsidian and locally of perlite; minor admixtures of tuff-breccia and bentonite; soft, poorly bedded; persists for about 2 miles along strike, then lenses out or grades into tuff	0–200
Unconformable on quartz monzonite	

Conditions of Deposition. Deposition of the Jackhammer and Pickhandle Formations was preceded by a long interval of erosion of the pre-Tertiary crystalline rocks, as is indicated by the beveled surface cut on these rocks prior to deposition of these formations, and by the red-weathered surface of quartz monzonite below these formations. In the Mud Hills area, arkosic sand and conglomerate of the Jackhammer Formation, derived from erosion of the pre-Tertiary rocks, was deposited on the weathered surface of quartz monzonite. This was soon followed by local deposition of volcanic ash and then by eruption of the basalt lava that now forms the top of the Jackhammer Formation.

Deposition of the Jackhammer Formation was followed by a violent interval of volcanic activity in middle(?) Miocene time that is represented by the Pickhandle Formation and associated Opal Mountain Volcanics. Some tectonic activity was apparently involved, as indicated by the occurrence of granitic breccias in the Pickhandle Formation.

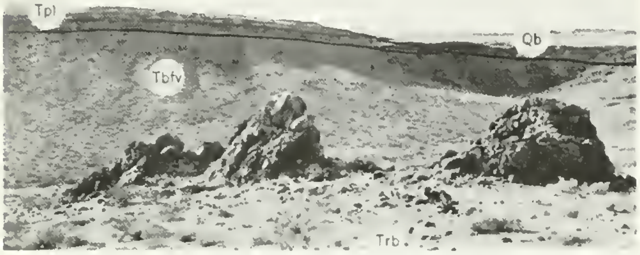

Photo 16. View west from Opal Mountain. Rhyolitic flow breccia (Trb) in foreground, overlain by tuff breccia covered by basalt float (Tbfv) overlain by chert and limestone (Tpl), in turn overlain by Black Mountain Basalt (Qb).

Photo 17. Prominent exposure of Pickhandle Formation capped by Black Mountain Basalt. View southeast across Black Canyon.

In the Mud Hills, deposition of the Pickhandle Formation started with deposition of granitic conglomerates and arkosic sandstones derived from erosion of nearby highlands of granitic bedrock. Elsewhere, volcanic ash, now tuff, was being deposited over wide areas and continued to accumulate throughout Pickhandle time. It must have been violently emitted with explosive volcanic gases from a number of volcanic vents. These became contemporaneously active in restricted areas, notably at the sites of the Gravel Hills and Black Canyon-Opal Mountain areas, to form volcanic fields. Scattered outlets also existed to the east in the Williams Plain area. Probably other vents were contemporaneously active north and east of the mapped area—notably east of Cuddeback Valley, Eagle Crag Mountains, and probably in the Calico Mountains.

The volcanic centers of the Gravel Hills, Black Canyon, and Opal Mountain areas are probably the major local sources of the pyroclastic sediments of the Pickhandle Formation; at least, the rock fragments of these sediments are of the same types as the Opal Mountain Volcanics exposed in those areas. Another important local source, especially of the pyroclastic rocks of the Mud Hills, was probably a volcanic center in or near the Calico Mountains to the southeast. This is suggested by the general eastward thickening of the Pickhandle Formation of the Mud Hills, and by the general increase in abundance and size of the lithic fragments of andesitic porphyry in the tuff eastward.

Most of the tuffs of the Pickhandle Formation were probably reworked and redeposited by streams; many of the rock fragments within it are rounded. Some of the loose pyroclastic material was probably washed down from higher areas by storms, and redeposited as pyroclastic mud flows in lower areas. The fine-grained stratified tuffs, such as those in the upper part of the formation in Black Canyon, were no doubt laid down in a lake. The arkosic sandstones and granitic conglomerates in the Pickhandle Formation were derived from erosion of nearby areas of granitic bedrock which may have been undergoing uplift.

The source of the great lenses of monolithic granitic breccia and the associated lenses of white rhyolitic felsite breccia in the upper part of the Pickhandle Formation at Owl Canyon is not definitely known. These are either large landslide masses, or debris flows, apparently from a high, steep mountain front, probably elevated by faulting during deposition of the Pickhandle Formation. The material that makes up the granitic breccias is similar to the quartz monzonite exposed north of the Mud Hills, which was presumably the source, although no major fault is apparent within this exposure of granitic rocks. Also, not far north of the Mud Hills, this quartz monzonite exposure contains patches of dark quartz diorite and hornblende diorite, but these rocks occur in none of the granitic breccias.

The white rhyolitic felsite associated with the granitic breccias was either intrusive into the granitic rock prior to deposition as landslides or debris flows in the tuff of the Pickhandle Formation, or was separate landslides or debris flows. However, the source of this rhyolitic felsite is unknown, as none is found in the quartz monzonite in place north of the Mud Hills. Dikes of similar rhyolitic rock occur several miles south in the Waterman Hills and southward nearly to Barstow, but in the Waterman Gneissic Complex and not in quartz monzonite.

Photo 18. Basal limestone lens of Jackhammer Formation resting on quartz monzonite exposed at right. North of Mud Hills at east border of Opal Mountain quadrangle.

It may be concluded that the large lenses of monolithic breccias of quartz monzonite and of white rhyolitic felsite are landslides or debris flows. Their presence within the tuffaceous rocks of the Pickhandle Formation indicates certainly that the mid-Tertiary volcanism was accompanied by local but violent tectonic activity. Rugged granitic mountains were formed, from which masses slid or flowed down into the basin in which pyroclastic material was being deposited.

The Pickhandle Formation appears to have been deposited in a large valley that extended from the site of the Gravel Hills southeastward through the sites of Black Mountain, Opal Mountain, Eastern Harper Valley, and the Mud Hills into the Calico Mountain area. This large valley became an undrained basin (the Barstow depositional basin or trough referred to by Bowen, 1954, p. 81), which subsided as it became filled with pyroclastic and sedimentary material during Miocene time. Pyroclastic rocks indistinguishable from those of the Pickhandle Formation were deposited over much of the area north of this subsiding basin, over the sites of Williams Plain and Superior Valley, and over the Pilot Knob-Eagle Crag areas. Lack of remnants of the Pickhandle Formation anywhere south and west of Harper Valley, and its absence in all wells drilled in that valley, suggest that it was never deposited in those areas.

Probable Age and Correlation. The Pickhandle Formation has yielded no fossils, so that its exact position in the Tertiary is uncertain. Its approximate age may be inferred from its stratigraphic position between the Jackhammer Formation, lower Miocene(?) below, and the Barstow Formation, late middle and upper Miocene, unconformably above; that is, the Pickhandle Formation is most likely, although questionably, middle or possibly early Miocene.

Pyroclastic rocks similar to the Pickhandle Formation and possibly equivalent to it in age are widespread throughout the central and western Mojave Desert region, and are commonly associated with silicic volcanic rocks.

To the east in the eastern Alvord Mountains, where a complete Tertiary section is exposed, the Pickhandle Formation is not recognized, but may be represented by several hundred feet of tuff overlying the basal red fanglomerate of the Tertiary sequence. This is overlain by a thick basalt flow and clastic sediments mapped by Byers * as the Barstow Formation.

In the western Mojave Desert region a pyroclastic formation recently mapped as the Gem Hill Forma-

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* Byers, F. M., Geology of the Alvord Mountain quadrangle; U. S. Geol. Survey Bull., Bull. 1089 A, 1960.

Photo 19. Panorama west across Salamon Canyon, eastern Mud Hills, showing granitic breccias (dark exposures) and tuff and volcanic breccia-conglomerates of Pickhandle Formation. Dark ledge near extreme right is limestone lens of Jackhammer Formation resting on light-colored quartz monzonite.

tion has been described by the writer** in the Rosamond Hills. This formation is the lower part of the Rosamond Series of Hershey (1902, p. 444), and is presumed to be of middle Miocene age. It is very similar to the Pickhandle Formation, and is likewise associated with rhyolitic volcanic rocks.

In the mountains northeast of Tehachapi Valley a pyroclastic unit named the Kinnick Formation by Buwalda and Lewis (1955, p. 147–148) has yielded the Phillips Ranch mammalian fauna described by Buwalda (1916, p. 77–79) that suggests middle Miocene (Hemingfordian) age. This formation is composed largely of tuff similar to that of the Pickhandle Formation. Its stratigraphic position is similar to that of the Pickhandle Formation, inasmuch as the Kinnick lies above the arkosic Witnet Formation of Buwalda and Lewis (1955, p. 147) and below the sedimentary Bopesta Formation of Buwalda and Lewis (1955, p. 148) which yielded the Cache Peak mammalian fauna of supposed late Miocene (Barstovian) age.

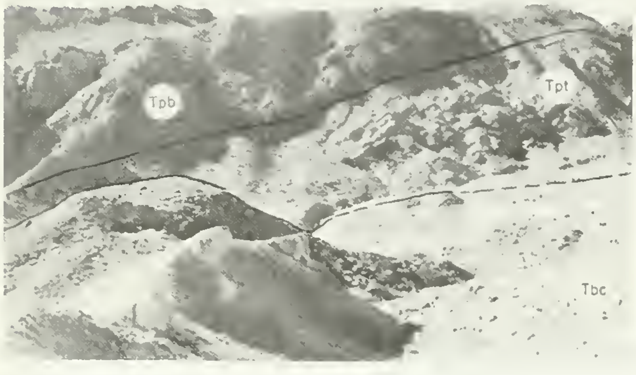

Photo 20. Pickhandle Formation exposed in Owl Canyon. View west showing granitic breccia (Tpb) overlying tuff breccia (Tpt) on volcanic conglomerate (Tbc).

OPAL MOUNTAIN VOLCANICS

Areal Distribution. In the vicinity of Black Canyon and Opal Mountain numerous masses of rhyolitic volcanic rocks occur within the middle(?) Miocene Pickhandle Formation as intrusive and extrusive flow-breccias. These rocks are named the Opal Mountain Volcanics, after Opal Mountain which lies within the type area.

The large volcanic field in the vicinity of Opal Mountain and the three forks of Black Canyon nearby to the northwest is designated the type locality of the Opal Mountain rhyolitic rocks because all phases of these rocks occur there. To the west in the Gravel Hills are two other exposed areas of these rocks, one in the central and the other in the western part. In the Williams Plain are scattered volcanic necks of rhyolitic rocks intrusive through granitic crystalline rocks; near the Williams pumicite quarry is a rhyolitic flow-breccia associated with the Pickhandle tuff. In the Mud Hills are several occurrences of volcanic rocks associated with the Pickhandle Formation.

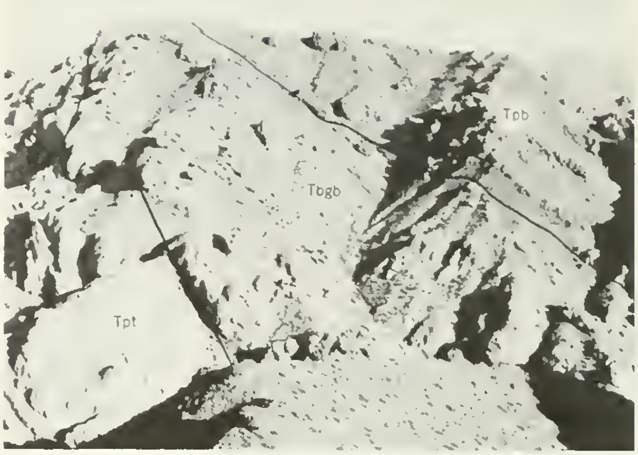

Photo 21. Pickhandle Formation exposed in Owl Canyon. View east showing red granitic breccia (Tpb) on gray granitic breccia (Tgb) on tuff breccia (Tpt).

Topographic Expression. Because of their extreme hardness, fine texture, and high silica content, the Opal Mountain rhyolitic rocks are highly resistant to weathering and erosion. Wherever they are exposed they form prominent, steep-sided, rocky, butte-like hills that protrude above a surface of generally low relief. The rocks are closely jointed and weather to angular, irregular fragments, and locally into platy blocks or slabs. These commonly accumulate as small talus slopes at the bases of the butte-like hills.

Lithology. The Opal Mountain Volcanics were mapped in the field as rhyolite. Several samples were determined petrographically to be quartz latite, based on the minerals present as phenocrysts, and it is likely that most if not all of these rocks are quartz latite rather than true rhyolite. Since nearly all phases of the Opal Mountain Volcanics were determined in the field, however, the rocks will be simply designated by the field name "rhyolitic rocks."

The Opal Mountain rhyolitic rocks vary in texture from vitreous through felsitic to subporphyritic. The rocks are physically either intact or brecciated. The intact phase, which may be either massive or flow-laminated, occurs only as intrusive plugs or dikes that fill volcanic vents. The brecciated phase occurs along the margins or pinch-outs of the intrusive plugs, and also as extrusive flow-breccias within the Pickhandle tuff.

The intact intrusive phase of the rhyolitic rocks is pink to tan, felsitic to fine-grained, and in some plugs slightly porphyritic, with phenocrysts of feldspar, quartz, and biotite up to 3 millimeters in size. The phenocrysts rarely exceed 20 percent of the volume of the rock. A sample of porphyritic intrusive rock from the large plug 2 miles north of Opal Mountain, and generally typical of the other larger plugs nearby, contains phenocrysts of plagioclase (oligoclase-ande-

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** Dibblee, T. W., Jr., 1958, Tertiary stratigraphic units of the western Mojave Desert, California: Am. Assoc. Petrol. Geol., vol. 42 no. 1, p. 135–144.

sine) and quartz, in a microcrystalline groundmass (average refractive index 1.53) composed of orthoclase, quartz, and plagioclase, in decreasing order of abundance.

The intact rhyolitic rock of the larger plugs is either homogeneous, and fractures into angular blocks, or is flow-laminated and fractures or cleaves along the laminae into platy slabs of various thicknesses. The flow-laminae are nearly always parallel to the walls of the intrusive plug and concentric around its center, although locally they are undulating or contorted. On the margins of many plugs the rhyolite is commonly brecciated; in others it is chilled to gray perlite.

The very small volcanic plugs, or the terminal wedges of some larger ones of irregular shape, are commonly composed of finely pumiceous rhyolitic glass of light gray color that weathers to rusty tan. In upper Black Canyon little plugs of this pumiceous rock are especially abundant. In some of these, flow-laminae and fracture cleavages that are concentric around their central cores are well formed as in the larger plugs of fine-grained rhyolite; in others the pumiceous rock is severely brecciated to form conspicuous rust-colored outcrops.

The brecciated phase of the rhyolitic rocks occurs along the margins of larger intrusions or at their terminal offshoot wedges or dikes, and also as flow-breccias. The intrusive or extrusive origin of the rock masses can be determined only by their field relationships with adjacent rocks. The brecciated rhyolitic rock is pinkish brown or dark maroon red color and appears generally darker than the intact phase. The brecciated rock is composed of angular fragments of all sizes of pink to maroon, massive to flow-laminated, subglassy to felsitic, rhyolitic rock embedded in a rhyolitic matrix to form a solid mass.

Some of the breccia and flow-breccia masses are bordered by zones of pinkish brown, glassy, rhyolitic rock that is commonly flow-laminated and contains spherulites as large as several inches in diameter. This rock is the more rapidly cooled phase of normal rhyolitic rock. It grades outward into marginal zones of perlite which generally contact the tuffaceous rocks that enclose the rhyolite masses.

Perlite generally occurs as the rapidly chilled marginal phase of the rhyolitic intrusive and extrusive bodies of Opal Mountain Volcanics. The perlite is a massive, nonporphyritic, nearly opaque, steel-gray, glassy rock with innumerable curved and spheroidal "onion-skin" fractures formed by rapid chilling. The rock is usually intact and only locally brecciated. The perlite is commonly formed along the base, top, and marginal pinch-outs of rhyolitic flow-breccia bodies, and around margins of intrusive rhyolitic masses. Perlite occurs in all four volcanic fields within the mapped area but is most widespread in the Black Canyon-Opal Mountain field. The locations of the various perlite deposits are indicated under Mineral Resources, and shown on the map.

In the Black Canyon-Opal Mountain volcanic field the vitreous rhyolitic rocks associated or in contact with perlite commonly contain layers of spherulites from one fourth to one inch in diameter that are scattered to numerous. The spherulites are usually lighter in color than the enclosing rock. Most are massive, but some show faint structure radiating from their centers; others show crude concentric structure.

Other layers of vitreous rhyolitic rock, especially some flow-laminated ones associated with perlite, contain large irregular-shaped rhyolitic nodules from 1 to about 6 inches in diameter. The nodules are of various shapes, usually irregular and commonly elongated parallel to the flow-laminae in the rhyolitic rock; many are intergrown with each other. The nodules, even those occurring in perlite, are composed of vitreous, fine-textured, granular, rhyolitic rock in colors varying from dark brown, maroon, and pink to green. Most are massive but those occurring in flow-laminated rhyolite are faintly laminated, with the laminae of the enclosing rock passing through the nodules. The laminae appear prominently on weathered surfaces of nodules. Some nodules are solid, but many contain in their centers small to large fissures and cavities filled with white opal, clear chalcedony, layered chalcedony (agate), ochre-colored jasper, or crystalline quartz, commonly interlayered in either flat or concentric laminae that form delicate patterns seen when the nodule is broken or sawed in half. A few contain calcite crystals or their chalcedony pseudomorphs. In this area the internal fillings of the nodules are always irregular, without the definite patterns formed in some from other regions.

Most of the siliceous nodules and spherulites occur within 1 mile west and south of Opal Mountain, adjacent to perlite zones in the rhyolitic flow-breccia. Other localities occur northeast of Opal Camp (Scouts Cove) and near the Hicks perlite quarry, as indicated under Mineral Resources.

At the northwest end of the Mud Hills 2 miles southwest of Coolgardie Camp are several outcrops of a dark-brown volcanic flow-breccia that is unlike any of those in the Black Canyon-Opal Mountain area. This breccia, which rests on quartz monzonite, is roughly 200 feet thick, and composed of angular fragments as much as 9 inches across of massive tan felsite embedded in a hard, dark-brown matrix. The top of this breccia is concealed by Quaternary gravels, but the breccia probably dips under the Pickhandle tuff or the Barstow Formation.

At the southern margin of the Mud Hills east of the mouth of Owl Canyon is a small Z-shaped exposure of brown porphyritic andesite intrusive into tuff of the Pickhandle Formation. The andesite is massive and locally brecciated. Phenocrysts make up about 30 percent of the rock, and consist of white plagioclase feldspar, potassium feldspar (sanidine), and flakes of biotite. The matrix is medium-brown, dense, and felsitic. It is similar to andesite flow-breccias occurring within the Pickhandle Formation in the east end of the Mud Hills just east of the Goldstone Road, in Lane Mountain quadrangle, and in the northwestern Calico Mountains.

Origin and Emplacement. The Opal Mountain Volcanics were apparently emplaced as a viscous magma in the many volcanic vents through which the pyroclastic material of the Pickhandle Formation was

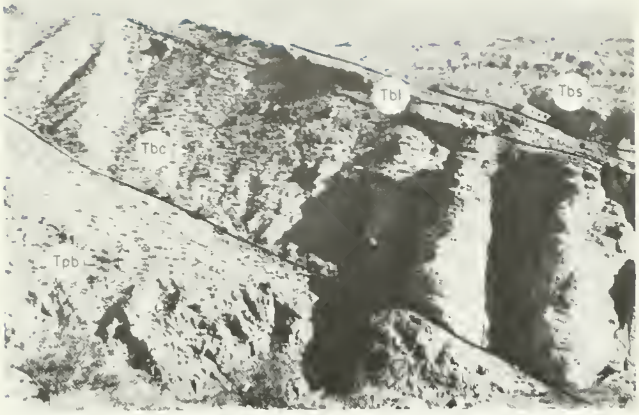

Photo 22. Owl Conglomerate Member of Barstow Formation (Tbc) unconformable on red granitic breccia (Tpb) of Pickhandle Formation. Conglomerate is overlain by algal limestone (Tbl) and sandstone and clay (Tbs) of Barstow Formation.

Photo 23. Typical exposure of Owl Canyon Conglomerate of Barstow Formation on the south flank of Barstow syncline. West Rainbow Canyon, Mud Hills.

emitted, plugging the vents during the later or final stages of the middle(?) Miocene volcanic activity, after the explosive gases had ceased to escape. The viscous rhyolitic lava was in part extruded at the surface from some vents and accumulated either as volcanic piles or as flows, as is indicated by the occurrence of thick rhyolitic masses or flow-breccias within the Pickhandle tuff. The intact phase, and some of the brecciated rock, solidified from the magma that filled the vents. The flow-breccia solidified from the extruded lava.

Age. Since the Opal Mountain rhyolitic rock occurs as intrusions into and as flow-breccias within the Pickhandle tuff in most of its exposures in the mapped area, most if not all of this volcanic formation must be the same age as the Pickhandle Formation, that is, middle (?) Miocene. The Opal Mountain rhyolitic rocks of the Gravel Hills and Black Canyon-Opal Mountain volcanic fields are definitely older than the Barstow Formation, because none of the rocks are intrusive into it, and water-worn clasts of the Opal Mountain rocks occur abundantly in the fanglomerate facies of the Barstow Formation in the Gravel Hills.

The age of the rhyolitic rock in the isolated plugs intrusive into the quartz monzonite in the Williams Plain area is uncertain. These rhyolitic masses are younger than the granitic rocks they intrude, but whether they are of Miocene or Pliocene age is a disputed question. Those occurring east of the quadrangle were inferred by McCulloh * to be of Pliocene(?) age, because in the southern part of the Calico Mountains similar rhyolitic rocks intrude all Miocene formations, including the Barstow Formation. However, the rhyolitic rocks of the Williams Plain area are all lithologically similar to and probably related to the Opal Mountain rhyolitic rocks of middle(?) Miocene age to the west. The relationship of at least one of these plugs to the Pliocene(?) Lane Mountain andesite appears to be well indicated a mile northeast of the Williams pumicite quarry, where a rhyolitic plug is partly overlain by Lane Mountain andesite.

BARSTOW FORMATION

The earliest application of the name "Barstow" to a stratigraphic unit was by O. H. Hershey (1902a, p. 369–70) when he mentioned the "Barstow Series" as a "thin, flat-lying valley formation extensively developed on the low hills on the north side of the Mojave River valley between Barstow and Daggett." He described a 59-foot thick, flat-lying section of this formation exposed in a railroad cut 1½ miles east of Barstow, but assigned no age to this formation. Two months earlier, a geologic sketch map of the west central Mojave Desert by Hershey (1902b, facing p. 2) showed the Quaternary of the Mojave River valley at Barstow and for several miles eastward. This map also showed outcrops of Tertiary rocks of the "Rosamond Series" near Rosamond and several miles north of Barstow, but it is doubtful if Hershey saw those north of Barstow. As seen by the writer, the type section of the "Barstow Series" briefly described by Hershey (1902a, p. 369–372) is an incomplete section of Pleistocene alluvium, and has been so mapped (Bowen, 1954, pl. 1; Dibblee, 1960b).

Soon after Hershey's papers were published, a large assemblage of mammalian fossils was discovered in the Tertiary stratified rocks prominently exposed in the Barstow syncline at the Mud Hills, 7 to 10 miles north of Barstow. J. C. Merriam of the University of California undertook a long series of excellent, now classic paleontologic studies of these fossils. In the course of these studies, he sent a student, C. L. Baker, to make field observations of the beds in which the fossils were found. Baker (1911, p. 345–47) described these beds and divided them into five members, as shown in a cross-section of the Barstow syncline at Rainbow Canyon. He referred the entire succession to the

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* McCulloh, T. H., Geology of the southern half of the Lane Mountain quadrangle, California. Ph.D. thesis, 1952. Univ. of California at Los Angeles.

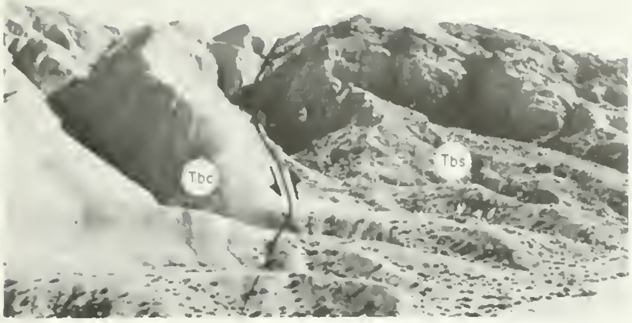

Photo 24. Barstow Formation exposed near mouth of east Rainbow Canyon. View east, showing clay and sandstone (Tb) in fault contact with Owl Conglomerate Member (Tbc) on south flank of Barstow syncline.

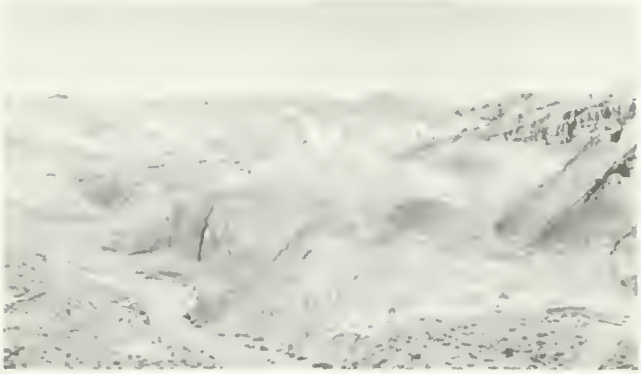

Photo 25. Lacustrine gray and tan clay shale of the lower part of the Barstow Formation on south flank of Barstow syncline. View north up east Rainbow Canyon, Mud Hills.

"Rosamond Series" earlier described by Hershey (1902a, p. 365–368), with a type section in the Rosamond Hills some 65 miles west of the Mud Hills. This is unfortunate, because the type Rosamond Series is unfossiliferous, so that its age within the Tertiary is unknown and its correlation with the beds of the Mud Hills is doubtful.

Merriam (1915, p. 252–254, 1919, p. 441–48) applied the term "Barstow Formation" to the Tertiary beds that contain the Barstow mammalian fauna in the Barstow syncline. He was either unaware of, or did not acknowledge, Hershey's usage of Barstow Series as valid by priority, perhaps because Hershey's description of it was meager, and it had never become established in the literature. On the other hand, Merriam's usage of Barstow Formation has become firmly established in paleontologic literature and has been recognized for over 30 years; it is now recognized as a valid formational name by the U. S. Geological Survey (Wilmarth, 1938, p. 119).

Barstow Formation as Defined by Merriam. In his final paper, Merriam (1919, p. 441) defined the Barstow Formation merely as the beds that contain the Barstow mammalian fauna, which he determined to be of upper Miocene age; he did not define its limits. This fauna was found only in the upper two of the five members of the "Rosamond Series" of the Barstow syncline described by Baker (1911, p. 342–347), or what he called the "fossiliferous tuff" and "resistant breccia" members. Merriam (1919, p. 441) thereby formally named and described these two members as the Barstow Formation. He suggested that the Barstow Formation be limited to these two members, but also indicated that the formation might include all the strata of the Barstow syncline.

Barstow Formation as Redefined. Detailed geologic mapping of the Tertiary strata of the Barstow syncline in the Mud Hills has revealed not only the presence of a major lithologic break, but an angular unconformity between the fossiliferous, predominantly sedimentary, strata (upper two members of Baker, 1911, p. 342–347) defined by Merriam (1919, p. 44) as the Barstow Formation, and the underlying unfossiliferous, predominantly pyroclastic strata (lower three members of Baker, 1911, p. 342–347). This stratigraphic break and unconformity thereby mark the base of the Barstow Formation as hereby redefined. The formation below this unconformity is assigned to the Pickhandle Formation already described.

The Barstow Formation is here defined as that sequence of deformed, stream-laid conglomerates, sandstones, lacustrine clays, and several thin tuffs, which lies unconformably above granitic breccia and tuff of the Pickhandle Formation, unconformably below flat-lying older alluvium of Pleistocene age, and which contains a mammalian fauna of late-middle and upper Miocene age.

Photo 26. Varicolored clay shale and sandstone beds of Barstow Formation exposed in Rainbow basin, Mud Hills. View northeast across axis of Barstow syncline. Dark hills in distant background formed by granitic breccias of Pickhandle Formation. Badlands on right capped by Pleistocene older alluvium.

The type locality of the Barstow Formation is here designated as the continuous section measured and described by Durrell (1953, Section A-A, pl. 4; fig. 12) just west of Solomon Wash in the Mud Hills (in Secs. 20 and 29, T. 11 N., R. 1 W.). All the 1,527 feet of fine-grained strata of Durrell's Section A-A are within the Barstow Formation, as here redefined, together with the 448-foot conglomerate of the top of the section. This is overlain unconformably by gravel of the older alluvium. This measured section does not include the basal beds of the Barstow Formation, but these are included in Durrell's Section B-B, in Ross Canyon about 4,000 feet west of Section A-A. In Section B-B, the basal unit of the Barstow Formation is composed of 28 feet of dark algal limestone, and the underlying 139 feet of basal granitic conglomerate. These strata lie with angular discordance on granitic breccia and tuff-breccia of the Pickhandle Formation. The total thickness of the Barstow Formation exposed in the area between Solomon and Ross Canyons is about 2,110 feet.

The prolific vertebrate fauna from the Barstow Formation has been obtained not from the type section, which is the only one completely exposed and free from structural complexities, but from exposures 2 to 5 miles west, within the Barstow syncline.

Areal Distribution. The Barstow Formation is most spectacularly exposed in the Barstow syncline in the Mud Hills in southeastern Opal Mountain quadrangle, the type area. Southeasterly, this formation crops out discontinuously off the quadrangle in the Calico Mountains. West and northwesterly from the Mud Hills, the Barstow Formation, although concealed by Quaternary alluvium and basalt extends under Harper Valley and Black Mountain, but again emerges in Black Canyon and crops out northwesterly for some 10 miles through the Gravel Hills in the Fremont Peak quadrangle nearly to the southern end of Cuddeback Dry lake.

Photo 27. View west in the Rainbow basin, Mud Hills. The Barstow Formation exposed in Barstow syncline is capped by Pleistocene older alluvium.

Topographic Expression. Differential erosion of tilted strata of various rock types in the Barstow Formation has produced colorful scenic badlands. The fanglomerates are eroded to hills strewn with loose cobbles and boulders, and better-indurated layers of conglomerate and conglomeratic sandstone form resistant outcrops. Tilted layers of harder sandstone crop out as prominent ledges, strike ridges, and dip slopes. The same applies to hard tuff beds and calcareous layers, which crop out even more prominently, especially where interbedded in softer clays. Intervals of clay shale are eroded to low rounded hills and badlands covered with a soft, fluffy clay soil almost devoid of vegetation.

Barstow Formation of the Mud Hills. In the Mud Hills the Barstow Formation is composed of nearly 3,000 feet of stream-laid conglomerates, sandstones, and lacustrine clay shales, together with several thin layers of localized limestone and tuff, and a basal conglomerate as thick as 1,000 feet. The beveled surface of these deformed strata is covered by a veneer of dissected Pleistocene alluvium, indicating that an unknown thickness of younger beds of the Barstow Formation has been eroded away.

The lowest part of the Barstow Formation is composed of cobble conglomerate exposed on both flanks of the Barstow syncline. It is here named the Owl Conglomerate Member of the Barstow Formation, after Owl Canyon. The type section is designated as the exposure on the north flank of the Barstow syncline between Owl and Solomon Canyons (in N½ Secs. 19 and 20, T. 11 N., R. 1 W., S.B.B. and M.). Along this exposure the conglomerate averages about 190 feet in thickness, with a maximum of 250 feet. It rests unconformably upon more steeply dipping granitic breccia and tuff of the Pickhandle Formation, and is overlain conformably by algal limestone and sandstone of the Barstow Formation. On the east side of Owl Canyon, the lower part of the conglomerate can be seen to buttress out up dip against the underlying granitic breccia, suggesting that the conglomerate thickens down dip. Immediately west of Owl Canyon the conglomerate wedges out, but reappears two miles northwest as a lentil as thick as 20 feet resting with angular discordance upon breccia and tuff of the Pickhandle Formation.

Photo 28. Rainbow Canyon fault separating sandstone beds (at left) from clay beds (at right) of Barstow Formation near axis of Barstow syncline. View west in Rainbow basin, Mud Hills.

The Owl Conglomerate Member exposed on the north flank of the Barstow syncline is gray, prominently bedded, in places cross-bedded, and moderately indurated. It is composed of rounded to subrounded fragments as large as 2 feet, mostly of quartz monzonite but some of aplite, pegmatite, quartz, and brown andesitic porphyry, embedded in a matrix of coarse-grained gritty arkosic sandstone. In places the conglomerate contains in its upper part lenses of fine-grained sandstone and clay shale of probable lacustrine origin, and some of these finer grained sediments contain scattered pumice fragments. Shale lenses in Owl Canyon range up to 50 feet thick.

On the south flank of the Barstow syncline, the Owl Conglomerate Member is more extensive and thicker, with the base unexposed except in the isolated exposure east of the mouth of Owl Canyon where it rests upon tuff and andesite of the Pickhandle Formation. In the exposures between Coon and Rainbow Canyons, nearly 1,000 feet of the Owl Conglomerate Member crops out, and an unknown additional thickness lies buried. The lithology of this member on the south flank of the syncline is about the same as on the north flank, except that much of it is red, and contains a greater admixture of clasts of brown andesitic porphyry, apparently derived from older Tertiary andesites. Also the conglomerate contains interbeds of red arkosic sandstones and, west of Rainbow Canyon, some red clays. At the mouth of Rainbow Canyon, the conglomerate contains a prominent lens, as thick as 50 feet, of thin-bedded gray lacustrine shale.

The rest of the Barstow Formation above the Owl Conglomerate Member is composed of sedimentary rocks that range from coarse fanglomerate to clay shales, with no orderly sequence for its entire areal extent. In general, this part of the Barstow Formation is composed predominantly of coarse stream-laid conglomerates or fanglomerates in the southwestern part of the Mud Hills and of sandstones and lacustrine clay shales in the northwestern, central, and eastern parts. Several layers of white tuff are fairly persistant in the fine-grained clayey and intermediate sandy facies.

Photo 29. Lacustrine clay (in foreground) overlain by buff sandstone (in background) of Barstow Formation on south flank of Barstow syncline. Lower, marker tuff (white bed) visible on skyline at center. View north across west Rainbow Canyon, Mud Hills.

The most complete and unbroken sequence of the Barstow Formation is the south-dipping section at the east end of the Mud Hills, just west of Solomon Canyon. This is the section measured by Durrell (1953, p. 32–36), and the designated type section of the Barstow Formation. The sequence follows in descending order:

Barstow Formation exposed just west of Solomon Canyon, Mud Hills, in secs. 20 and 29, T. 11 N., R. 1 W.

	Thickness (feet)
Unconformably overlain by older alluvial gravel.	
Conglomerate and sandstone: light gray-brown to rusty yellow, poorly consolidated, ill-sorted, cross-bedded; conglomerate with subrounded clasts up to 14 inches, chiefly of granitic rocks and of brown andesite, and some quartzite, hornfels, and quartz; some sandstone and conglomerate layers locally hard and calcareous or ferruginous; sandstone predominates in basal portion; of fluviatile origin	448
Limestone: gray, crudely laminated, contains algal material; partly silicified to gray and black chert	28
Sandstone: light-gray, well-bedded, fine- to medium-grained, arkosic; minor interbeds of green clay, impure limestone and tuff	50
Tuff: white, massive, fine-grained, rhyolitic (lower marker tuff?)	4
Sandstone and clay: sandstone light-gray, fine-grained in thin beds, and interbedded clay, gray to green-gray; some thin calcareous beds; some brown bentonite	197
Claystone: green, thin-bedded, argillaceous to sandy; contains thin layers of white-weathering calcareous nodules and lenses of limestone 1 to 4 feet thick	265
Bentonite: brown, massive, with thin, white tuff beds	85
Limestone: brown, porous, ferruginous, sandy, interbedded with green claystone	65
Claystone: green, thin-bedded, with white calcareous nodules	45
Bentonite: brown, massive	30
Claystone: green, with white-weathering nodular limestones and calcareous nodules	145
Sandstone and claystone, alternating: sandstone gray and green, thin-bedded, fine- to medium-grained; claystone green and buff, thin-bedded; contains some sandy limestone	336
Claystone: yellow and greenish-gray, thin-bedded, some thin sandstone beds	60
Claystone: yellow and greenish-gray, with thin layers of limestone and of strontianite nodules, few thin tuff layers	60
Sandstone: green and gray, arkosic, with some interbeds of green and red nodular clay	25
Tuff: white to gray, calcareous, fine-grained, rhyolitic	0–4
Sandstone: light-gray, fine- to coarse-grained, pebbly, tuffaceous, with pumice fragments	140
Algal limestone: dark-gray, irregularly bedded, composed largely of algal(?) deposits, probably calcareous tufa; locally interbedded in sandstone like that above	30
Conglomerate (Owl Conglomerate Member): gray to green-gray, crudely and locally cross-bedded, moderately to poorly consolidated, composed of subrounded cobbles and boulders of quartz monzonite, some of aplite, pegmatite, and rarely of brown andesitic porphyry	137
Total aggregate thickness of Barstow Formation	2,154

Unconformably underlain by granitic breccias and tuffs of Pickhandle Formation.

Barstow Formation exposed on south flank of Barstow syncline between east and west Rainbow Canyons, Mud Hills in secs. 24 and 25, T. 11 N., R. 2 W.

	Thickness (feet)
Unconformably overlain by Quaternary gravel and sand.	
Claystone: green-gray, massive, silty, exposed in axis of Barstow syncline	50
Claystone: red, massive, silty	50
Clay shale: gray, green, and light-red; well-bedded, argillaceous to silty; contains thin interbeds of green arkosic sandstone, calcareous sandstone, cream-white limestone, and calcareous tuff	450
Tuff (lower marker tuff bed): white, moderately hard, massive, fine-grained, composed of rhyolitic glass shards, and scattered grains of quartz and a green material	5
Sandstones and clays, interbedded: sandstones gray, green, buff, fine to coarse, arkosic; become more numerous and coarsen westward, decrease and lens out eastward; clays gray, green, with thin, scattered interbeds of cream-white limestone and calcareous tuff	500
Conglomerate: composed of granite boulders in gray arkosic sandstone matrix; grades laterally eastward into arkosic sandstone	50
Clay shales and sandstones, interbedded: clay shales light-gray, green to buff, well-bedded, argillaceous to silty, gypsiferous, contain several thin layers of limestone and tuff; sandstones buff to light-gray, well-bedded, fine- to medium-grained, arkosic, interbeds decrease downward	650
Clay shale: similar to that above; scattered interbeds of buff arkosic sandstone and thin layers of tan limestone	500
Conglomerate (Owl Conglomerate Member): moderately to poorly consolidated, cross-bedded; composed of subrounded boulders of granitic rocks and less abundant ones of brown andesite porphyry, aplite, pegmatite, and quartz, in a matrix of coarse red arkosic sandstone	400
Clay shale (Owl Conglomerate Member): gray to buff, thin-bedded, gypsiferous; interbedded with light buff fine-grained arkosic sandstone	80
Conglomerate (Owl Conglomerate Member): same lithology as above; base not exposed	300
Total exposed thickness of Barstow Formation	3,035

At the west end of the Mud Hills, the upper marker tuff is overlain by about 1,000 feet of sediments composed of alternating light-gray to red, soft, fine to coarse, pebbly, arkosic sandstones; green and red silts and clay shales; several hard, calcareous and silicified tuffaceous beds, and several limestone strata as thick as 5 feet. In these sediments lateral changes are so rapid that there is no defined sequence, even for this small area. These strata have yielded the bulk of the Barstow fauna described by Merriam (1919, p. 438–585).

Barstow Formation of the Gravel Hills. The Barstow Formation exposed in the Gravel Hills is predominantly coarse alluvial gravel or fanglomerate. Its maximum thickness is 4,500 feet along the southwestern part of these hills; northeastward it thins rapidly to a few hundred feet of alluvial fanglomerate that laps onto pre-Tertiary crystalline rocks.

Photo 30. Barstow Formation in Barstow syncline capped by Pleistocene older alluvium. Dark bed near syncline axis is red clay. Hard calcareous bed in foreground. View east in Rainbow basin, Mud Hills.

The lowest part of the Barstow Formation of this area is shale and sandstone exposed only in Black Canyon, and of sandstone exposed only in the central part of the Gravel Hills.

In Black Canyon, about three miles from its mouth, the lowest 300 feet of the Barstow Formation is light-gray, thin-bedded clay-shale of lacustrine origin. It grades downward through thin interbeds into the underlying white tuff of the Pickhandle Formation, with the contact mapped arbitrarily at the old well in Black Canyon. This shale is much contorted on the southeast wall of the canyon, probably by the action of landslides slipping down from Black Mountain above. Northwesterly the shale presumably grades laterally through sands into volcanic fanglomerate. All but the lowest part of this shale unit is exposed in the core of the large anticline in Sec. 16, T. 32 S., R. 44 E., west of lower Black Canyon. In both places the shale grades upward through interbeds into bedded gray-to-tan arkosic sandstone, which in turn grades upward into conglomerate. Three miles above the mouth of Black Canyon, this sandstone is about 400 feet thick and grades laterally northwestward into volcanic conglomerate. Near the top, this sandstone contains a bed of hard white tuff, 1 to 3 feet thick. In the anticline west of lower Black Canyon the sandstone is about 150 feet thick and contains several beds, from 1 to 12 inches thick, of pumiceous tuff. This sandstone is overlain by a flow of black olivine basalt as thick as 500 feet.

In the east central Gravel Hills, the lowest 700 feet of the Barstow Formation is composed of light-gray, well-stratified, fine- to coarse-grained, tuffaceous sandstone containing grit and fragments of rhyolite, dacite, and pumice lapilli. Near the middle of this unit is a lens of quartz monzonite breccia as thick as 200

Photo 31. Closer view of axis of Barstow syncline shown in photo 30.

feet, traceable for 1½ miles, which is similar to those in the Pickhandle Formation in the Mud Hills. Westward along strike this sandstone grades laterally to a granitic boulder fanglomerate which eventually overlaps on the Pickhandle Formation and associated rhyolitic rocks to the northwest. Northeastward along strike this sandstone becomes overlapped with increasing angular discordance by the overlying volcanic fanglomerate facies of the Barstow Formation.

The fanglomerate or gravel facies of the Barstow Formation exposed in the Gravel Hills is divisible into two distinct subfacies: (1) granitic fanglomerate, and (2) volcanic fanglomerate. They interfinger with each other abruptly along a line extending northwesterly through the Gravel Hills.

The granitic fanglomerate and gravel comprises practically all the Barstow Formation exposed throughout the southwestern portion of the Gravel Hills, where its thickness is some 4,500 feet; it thins northward. This subfacies is gray, crudely bedded, and ranges from coarse boulder fanglomerate and breccia to friable pebbly arkosic sandstone. Coarse boulder fanglomerates predominate in the western exposures, giving away eastward through cobble gravels to predominantly gritty arkosic sandstones in lower Black Canyon. The clasts, embedded in arkosic grit, are subrounded to angular, and range up to 8 feet in diameter. They are composed of granitic rocks, mostly quartz monzonite, but with some aplite, pegmatite, quartz diorite, and diorite, similar to those rocks in place in the Fremont Peak Range to the west, the probable source area. In the western exposures are increasingly greater admixtures of clasts of tan quartz latite porphyry of the type now exposed as dikes there.

Volcanic fanglomerate and gravel subfacies comprise all of the Barstow Formation in the northeastern Gravel Hills northwesterly from Black Canyon, and part of the fanglomerate facies in the northwestern part of these hills. This subfacies is pinkish-gray and is composed of rounded to subrounded fragments of volcanic rocks ranging up to five feet in diameter in a poorly consolidated matrix of predominantly volcanic detrital grit. The fragments are composed largely of reddish, pinkish, and greenish-brown flow-banded to massive felsitic and porphyritic rhyolitic rocks similar to those of the Opal Mountain Volcanics. Some fragments of andesitic porphyry and basalt are present, as well as fragments of vein chert, jasper, and opal of volcanic origin.

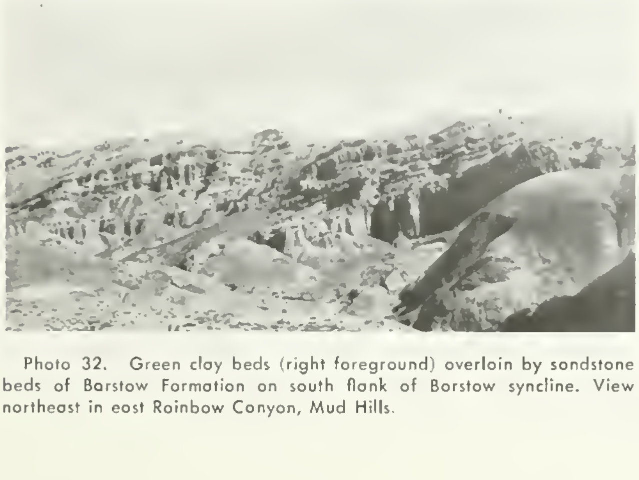

Photo 32. Green clay beds (right foreground) overlain by sandstone beds of Barstow Formation on south flank of Barstow syncline. View northeast in east Rainbow Canyon, Mud Hills.

The volcanic fanglomerate and gravel subfacies in the northeastern Gravel Hills is several thousand feet thick at the line along which it interfingers with the granitic subfacies. Northwestward it thins, rapidly coarsens, and overlaps the basal sandy facies of the Barstow Formation, Pickhandle Formation, and Opal Mountain Volcanics onto granitic basement rocks. The general northward coarsening and thinning of this volcanic fanglomerate indicates derivation from an area of older Tertiary volcanic rocks to the north or northeast.

In the alluviated part of Harper Valley, four wells were drilled in and near Harper Dry Lake; three encountered the Barstow Formation below the Black Mountain(?) Basalt. The Barstow Formation in these wells was found to consist of alternating granitic gravel or fanglomerate, arkosic sands, and green and reddish clays similar to those exposed in lower Black Canyon. The formation was found to thin in a southwesterly direction, as the most northeasterly well failed to reach the base of the Barstow Formation at 1,117 feet, whereas two others entered gneissoid basement rocks below the Barstow Formation. The other, the most southeasterly well, passed from basalt directly into gneiss at 480 feet.

Conditions of Deposition. The alluvial sediments and lacustrine clay shales of the Barstow Formation were deposited as the Barstow depositional basin continued to subside after being filled with pyroclastic sediments of the Pickhandle Formation. The violent and widespread volcanic activity prevalent in this region in Pickhandle time ceased in Barstow time, except for a local eruption of basalt near the site of Black Canyon, and for occasional lingering outbursts of ash as indicated by the presence of several thin tuff beds in the Barstow Formation. However, tectonic activity persisted and became so widespread and severe just prior to deposition of the Barstow Formation that it involved the Pickhandle Formation, as is indicated by the generally unconformable relationship of these two formations. The coarse detrital sediments that constitute much of the Barstow Formation are clear evidence that tectonic activity was continually producing rugged highlands adjacent to the Barstow depositional basin throughout the interval in Miocene time during which this formation accumulated.

The presence of remnants of the Pickhandle Formation or its equivalents in areas farther north than the Barstow Formation, and the absence of the Pickhandle Formation in areas to the south, at least within the mapped area, suggests that the Barstow depositional basin shifted southward in late Miocene or Barstow time. Also during that time the valley of sedimentation formed by this subsiding basin became narrower, as is indicated by the more restricted north-south extent of the Barstow Formation compared to the underlying Pickhandle Formation. There is no evidence that the Barstow Formation was ever deposited on the south or southwest side of Harper Valley, nor to the north of present exposures of this

Photo 33. Sandstone beds of Barstow Formation on south flank of Barstow syncline. East Rainbow Canyon, Mud Hills.

formation, as it coarsens and thins out rapidly against older, mostly pre-Tertiary rocks of these areas. These relations indicate that during Barstow time this basin became more strongly accentuated as a downwarping trough with an axis that became well defined. This axis of downwarp must have passed through the area where the Barstow Formation is thickest, that is through the Barstow syncline of the Mud Hills, thence northwest along the northeastern margin of Harper Valley and southwestern margin of the Gravel Hills.

In most of the Barstow basin, accumulation of the Barstow Formation started with deposition of coarse fanglomerate, such as the Owl Conglomerate Member now exposed in the Mud Hills. This was apparently deposited as alluvial fans derived largely from mountains of granitic rocks that must have risen to the south and to the north. However, farther west, at the site of lower Black Canyon, sedimentation started with fine muds accumulating in a lake that formed at the end of Pickhandle time. Streams flowing into this lake deposited deltaic sands.

In the Gravel Hills area northwesterly from Black Canyon, the coarse detrital sediments of the Barstow Formation were deposited continuously as alluvial fans in the northwestern part of the Barstow basin as it subsided. The fanglomerate of granitic and quartz latite detritus accumulated as probable eastward-sloping alluvial fans derived from rising mountains of these basement rocks to the west and southwest. And at the same time, the fanglomerate of volcanic detritus was accumulating as probable southward-sloping fans derived from a rising highland of Tertiary volcanic rocks to the northeast. Although some of this volcanic detritus may have been derived from the Opal Mountain Volcanics now exposed in the Opal Mountain-Black Canyon and Gravel Hills areas, most of it must have come from a source farther northeast, presumably the widely exposed Tertiary volcanic terrane of the Eagle Crag Mountains northeast of Superior Valley. Thus it appears that the granitic fanglomerate and the volcanic fanglomerate were each deposited as piedmont alluvial fans derived from highland sources on opposite sides of the Barstow basin.

In the Mud Hills, fanglomerate of granitic detritus continued to accumulate as alluvial fans in the southwestern part of this part of the Barstow basin after deposition of the basal Owl Conglomerate Member, as is indicated by the overlying fanglomerate now exposed in the south flank of the Barstow syncline. This fanglomerate was presumably derived from a highland area of granitic rocks south and southwest of the present Mud Hills. The source of the fragments of andesite porphyry in this fanglomerate may have been the Tertiary andesite porphyry now exposed in the Waterman Hills, Barstow quadrangle. The sandstone facies of the Barstow Formation of the Mud Hills accumulated as alluvial outwash in the lower floodplain areas of the Barstow basin. The clay shale facies, and its thin strata of calcareous rocks, no doubt accumulated under waters of a large shallow lake that flooded the lowest parts of the Barstow basin during most of late Miocene time.

Photo 34. Lacustrine gray, green, and red clays of Barstow Formation on south flank of Barstow syncline. Uppermost white bed at left center is lower marker tuff. Hard bed at center is limestone. View east across lower Owl Canyon, Mud Hills. Calico Mountains in distance.

Photo 35. View northwest from axis of Barstow syncline in east Rainbow Canyon, Mud Hills. Red clays of Barstow Formation at left and center foreground, underlain by sandstone beds. Owl Canyon fault shown at right between clays and sandstone beds.

Photo 36. View southeast at Owl Canyon fault (center) between light gray and buff sandstone beds at left and red clays at right, near axis of Barstow syncline. East Rainbow Canyon, Mud Hills.

Photo 37. Clays and sandstone beds of Barstow Formation near axis of Barstow syncline. Hard white bed at left center is lower marker tuff. View west in west Rainbow Canyon, Mud Hills.

Merriam (1919, p. 444) inferred that the numerous fossil remains indicate that large herds grazed on plains covered by luxuriant grasses dependent on a warm climate of wet and dry seasons. According to M. C. McKenna (*in* Taylor, 1954, p. 70), "the large numbers of species and individuals of the grazing animals, such as horses, camels, and antilocaprids, and the variety of carnivores of the Barstow fauna are strongly reminiscent of the present fauna of the African savannas, with grassy plains and scrub forest."

Age and Correlation. The fossil vertebrate fauna from the Barstow Formation exposed in the Mud Hills is one of the largest found in the Cenozic rocks of North America, and has been studied by many vertebrate paleontologists. It has been described in detail by Merriam (1919), and Frick (1937). Merriam (1919, p. 441–448) described it as the Barstow fauna, assigned a late Miocene age to it, and designated it as the type or standard fauna of the late Miocene Barstovian provincial age of the North American continental Tertiary.

The locations and stratigraphic positions of the fossil remains collected from the Barstow Formation in the Barstow syncline and described by Merriam (1919) are uncertain because no usable large scale map of the area was available and the geology was not then mapped. However, relocation of these localities by the U. S. Geological Survey and detailed mapping of the geology by the writer indicate that nearly all are from greenish, clayey, and sandy beds of the upper part of the formation (fossiliferous tuff member of Baker, 1911), or the part stratigraphically above the lower marker tuff bed or its equivalent horizon. Additional fossil material collected from these localities by Chester Stock has been identified by G. E. Lewis of the U.S. Geological Survey. These localities are shown on the accompanying geologic map of the Mud Hills. A list of mammalian fossils identified by G. E. Lewis from these localities appears below, along with a brief statement concerning their age significance.

The most common fossils of the Barstow fauna are bones and teeth of the species *Merychippus intermontanus*, a small three-toed horse. Also abundant are bones and horns of the antelope *Merycodus*, and bones of camels. The Barstow fauna is regarded by vertebrate paleontologists as being equivalent or possibly slightly younger than the Cache Peak fauna (also Barstovian) found in the Bopesta Formation near Tehachapi (Buwalda and Lewis, 1955, p. 148), and older than both the Ricardo fauna from the Ricardo Formation and the Mint Canyon fauna, both of which are assigned to the early Pliocene Clarendonian provincial age (Savage, Downs and Poe, 1954, chap. III, p. 45–48).

The Barstow Formation yielded remains of seven mammalian species from four localities northwest of Black Canyon. Three of these localities are located on the geologic map of quadrangle. The seven species of vertebrates listed by G. E. Lewis as collected by the Mojave Project in the Black Canyon area (listed below) occur also in the Barstow fauna of the Mud Hills.

A small nonmarine molluscan fauna of 11 species from mudstone and tuff of the upper part of the Barstow Formation from the Mud Hills has been described by D. W. Taylor (1954, p. 67–77, pl. 20), but their age significance was not determined.

Plant remains are notably scarce in the Barstow Formation. The only one known is a sabal palm that indicates a type of vegetation similar to the present vegetation of the warmer parts of northern Mexico, as stated by Savage, Downs, and Poe (1954, p. 48).

Remains of fresh water diatoms have been found in the lakebed, clay shale facies of the Barstow Formation of the Mud Hills but are not yet studied. Others were found at a locality in Black Canyon, about 3 miles N. 77 W. of Opal Mountain, from tuffaceous mudstone 20 feet above the 2-foot marker white tuff bed. The species from this locality are listed and their age significance is indicated in the accompanying report by K. E. Lohman.

Stratigraphic Paleontology of the Barstow Formation in the Mud Hills Area, San Bernardino County, California

by G. Edward Lewis [*]

Merriam (1911, p. 167) first described the fauna of Hershey's "Rosamond" (1902, pl. 1) in the Mud Hills area as coming from the "Mohave beds", but later (1915, p. 252–254; 1919, p. 441–448) used "Barstow" as a *faunal* and *formational* name for these same vertebrate fossils and for the rock unit in which they were found. The "Barstow" fauna so effectively described by Merriam has been generally accepted by paleontologic specialists in the North American continental Tertiary as being late Miocene in age (Wood and others, 1941, p. 12, 14, pl. 1; Simpson, 1933, p. 90).

Following Merriam's classic researches, by far the most extensive collections of Barstow fossils from the Mud Hills area have been made by Childs Frick and his associates (1926, 1937) but only quarry names have been published; precise geographic location and stratigraphic results are not yet available, although the published descriptions of part of the abundant material in these collections indicate that many specimens came from the source beds of the bulk of Merriam's collections.

Mojave project collections from the Mud Hills area. All of the collections made by the Mojave project of the U.S. Geological Survey comprise a fauna comparable to most of Merriam's late Miocene Barstow fauna. Like most of Merriam's, these new collections come from the upper part of the Barstow Formation as it is defined in the accompanying report by Dibblee of the Mud Hills area. Some new species are represented, but the fauna as a whole is typically late Miocene in age. The same two species of *Merychippus* occur throughout the upper part of the Barstow Formation, above Dibblee's "lower marker tuff bed," as do most of the other genera and species of Merriam's fauna of the Barstow, so there is no cogent evidence for zoning this part of the formation. None of the genera or species generally accepted as diagnostic of the Pliocene nor any diagnostic of the middle Miocene was found by U.S. Geological Survey collectors in the upper part of the Barstow Formation up to 800 feet above the "lower marker tuff bed" of Dibblee in the Mud Hills (sometimes called the "Barstow syncline") area.

It should be stated, however, that the U.S. Geological Survey collections from the Barstow Formation of the Calico and Alvord Mountain areas in the Mojave Desert have yielded middle Miocene fossils: for example, in the Alvord Mountain area (Lewis, in Byers, 1960, p. 32–33), *Brachycrus buwaldi* and, 500 feet lower, stratigraphically, *Merychippus tehachapiensis*, were found; these species are confined to beds of the Barstow Formation stratigraphically below the lowest level represented in the Survey collections from the Mud Hills area, all of which came from above Dibblee's "lower marker tuff bed." Therefore Lewis (1964, p. D21) concluded that the Barstow Formation contains at least three distinct faunas, the oldest of which is characterized by the presence of *Merychippus tehachapiensis* of middle Miocene (Sheep Creek) age.

Discussion. Frick described *Hemicyon barstowensis* from the "Barstow Miocene . . . our so-called Hemicyon stratum" (1926, p. 27–29), and *Hemicyon californicus* from the "*Hemicyon* Stratum, Barstow Miocene" (1926, p. 34). A subsequent publication by Frick (1937) refers to the "'*Hemicyon* Stratum'" or "'Hemicyon Stratum'", but no stratigraphic information is given other than citing this term. A fossiliferous tuff bed that yielded vertebrate remains at U.S.G.S. Fossil Vertebrate Localities (Red Nos.) D310, D316, and D317 [†], Dibblee's "upper marker tuff bed," may be the same bed as the "*Hemicyon* Stratum" of Frick.

Schultz and Falkenbach (1949, p. 80) show the distribution of *Brachycrus buwaldi* and *Brachycrus buwaldi barstowensis* in the Frick collections from the Mud Hills area as equivalent in age and stratigraphic position to the Sheep Creek Formation of the middle part of Lugn's Hemingford Group in the west-central Great Plains (1940, p. 242; 1941, p. 76). The Sheep Creek (in this sense) local fauna is generally considered to be of middle Miocene age (Wood and others, 1941, pl. 1, p. 31). Earlier, Schultz and Falkenbach (1940, p. 224–228) stated that 113 specimens of "*Brachycrus* remains in the Barstow area are recorded only from the Green Hills horizon or Second Division which underlies the later deposits including the '*Hemicyon* Stratum' of the First Division." But *B. buwaldi* occurs 500 feet higher stratigraphically than *M. tehachapiensis*, so *B. buwaldi* and the "Green Hills" local fauna of Frick, Schultz, and Falkenbach are younger than the Sheep Creek local fauna, and therefore are probably of late Miocene age but appreciably older than the late Miocene fauna that occurs above Dibblee's "lower marker tuff bed".

The horned ruminants of the Frick collection are recorded from various named quarries not precisely located, without conventional stratigraphic data (Frick, 1937, p. 5, 7). The U.S. Geological Survey field investigations, with only the foregoing data available, thus could not certainly determine the stratigraphic positions of the Frick localities.

Specimens of vertebrate fossils were collected at 12 localities, and identified generically, together with all those previously described, in an earlier publication (Lewis, 1964, p. D19–22).

In addition to the Survey collections, I have identified certain undescribed fossil vertebrate specimens from the "Green Hills" local fauna that were collected in the Mud Hills area for the Webb School and kindly placed at my disposal by Mr. Ray Alf. He, with Mr. R. A. Sheppard of the U.S. Geological Survey, determined that the three localities involved occur in the following stratigraphic order, from above downward:

Locality WS Bar 5, the highest stratigraphically, cannot be placed precisely because of structural complications but is between 375 and 475 feet below Dibblee's "lower marker tuff bed." It yielded several cheek teeth of *Merychippus stylodontus* Merriam and fragmentary camelid bones.

Locality WS Bar 6, about 675 feet below the "lower marker tuff bed," also yielded cheek teeth of *M. stylodontus* plus a radius, ulna, metacarpal, and splints assumed to belong to the same species, together with fragmentary hind leg and foot elements of a camelid identified as ?*Protolabis* sp.

Locality WS Bar 4, the lowest stratigraphically, is about 800 feet below the "lower marker tuff bed" and offers the most interesting paleontologic age evidence of all three localities. It yielded not only cheek teeth of *M. stylodontus* and a proximal phalanx of ?*Protolabis* sp. but also two significant oreodonts. A right maxillary fragment with the second and third molars is referred to *Brachycrus buwaldi* (Merriam). A maxillary fragment with the incomplete second and third upper molars, and a ramal fragment with the first and second lower molars are referred to *Merychyus* (*Metoreodon*) cf. *M.* (*M.*) *relictus* Matthew and Cook (including the two subspecies described by Schultz and Falkenbach, 1947, p. 241–244); I am unable to distinguish the Webb School specimen from the unique type of the subspecies *M.* (*M.*) *r. fletcheri* Schultz and Falkenbach previously reported from the Barstow of the Mud Hills area (1947, p. 244). The specimen I previously referred to ?*Merychyus* sp. (in Byers, 1960, p. 33) from U.S.G.S. Locality (Red No.) D321 in the Alvord Mountain area is possibly conspecific with the specimen from *WS Bar 4* and definitely referable to *M.* (*Metoreodon*) sp. but occurs there together with *Merychippus tehachapiensis* of Sheep Creek age, 500 feet lower stratigraphically than *Brachycrus buwaldi* from U.S.G.S. Locality (Red No.) D319 in the Alvord Mountain area which correlates with *WS Bar 4* in the Mud Hills area.

Evidence for three distinct faunas in the Barstow Formation. Merriam's collections were the basis for the definition of the called "Barstovian" late Miocene "provincial age" and "local fauna" of the Barstow Formation. Although "*Merycochoerus*" (= *Brachycrus*) was specifically listed as one of the "Barstovian" faunal elements (Wood and others, 1941, p. 12), the U.S.G.S. and Frick collections (Schultz and Falkenbach, 1940) leave no reasonable doubt that *Brachycrus* does not occur with the first, youngest Barstow vertebrate fauna in the upper part above Dibblee's "lower marker tuff bed," but is one element of a second, older fauna. No presently available evidence bears out the view of Schultz and Falkenbach (1949, p. 80) that the poorly preserved, unique specimen of *Merychyus (Metoreodon) relictus fletcheri* indicates another fauna that occurs stratigraphically between these two faunas. But a third, and the oldest, Barstow vertebrate fauna characterized by the presence of *Merychippus tehachapiensis* does occur below the *Brachycrus* zone in the Alvord Mountain area, as demonstrated above.

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[*] Publication authorized by the Director, U.S. Geological Survey. Revised 1967.

[†] U.S. Geological Survey Fossil *Vertebrate* Localities are always listed by color code as "*Red* Numbers", and the capital "D" preceding a number shows that it is catalogued at the Denver Laboratory of the Branch of Paleontology and Stratigraphy. The corresponding 12 numbered fossil localities shown on Dibblee's geologic map of the Mud Hills (Plate 2, in the accompanying report) are those in parentheses after the following "Red Numbers": D307(=11), D308(=8), D309(=9), D310(=1), D311(=2), D312(=3), D313(=4), D314(=5), D315(=6), D316(=7), D317(=10), and D318(=12).

Fossil Vertebrates from the Black Canyon Area. The scanty collections made by the Mojave project of the U.S. Geological Survey from the Black Canyon area represent elements of the Barstow fauna described by Merriam (1919). Specimens were collected at four localities.

Two of these localities (Red) Nos. D303 and D304, occur just above a tuff which may correlate with either Dibblee's "lower" or "upper marker tuff" in the Mud Hills area. The specimens collected at locality (Red) No. D305 also represent a typical Barstow assemblage; those from (Red) No. D306 may be somewhat older.

Discussion. All the fossil vertebrates collected by the U. S. Geological Survey in the Black Canyon area represent genera and species that also were collected in the upper part of the typical Barstow Formation in the Mud Hills area. It seems probable that the Barstow rocks in the Black Canyon area originally were continuous with those of the Mud Hills area, and safe to assume that localities (Red) No. D303–D305 inclusive may be correlated with that part of the Barstow Formation above the "lower marker tuff bed" as mapped by Dibblee in the Mud Hills area.

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Photo 38. Locustrine cloys and tuffoceous sholes of lower port of Borstow Formotion. Southeost woll of Block Conyon.

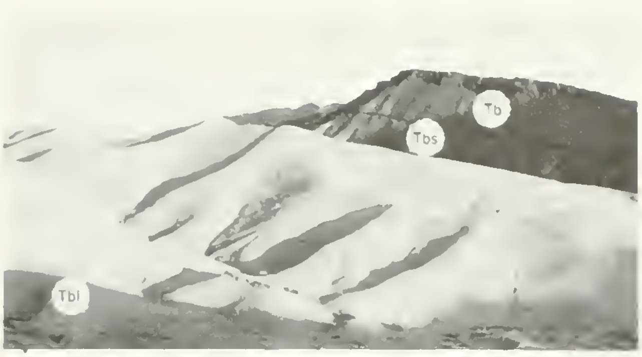

Photo 39. Locustrine cloy shole (Tbl) of Borstow Formotioo, overloin by sondstone (Tbs) ond bosolt flow (Tb) of Borstow Formotion. South flonk of Block Conyon onticline west of lower Block Conyon.

Miocene Diotoms From the Block Conyon Areo
by Kenneth E. Lohmon

A collection of mudstone from the Black Canyon area in the same wash as vertebrate locality numbers 462 and 463, within a hundred yards of them and in the same general stratigraphic position, has yielded a diatom assemblage of over 25 identified species and varieties. The locality data follows:

U. S. Geological Survey Diatom Locality 3492. Black Canyon, NW¼ sec. 11, T. 32 S., R. 44 E., Mt. Diablo Base and Meridian, San Bernardino Co., California. About 3 miles N. 77°W. from Opal Mountain. Highly mottled gray and light brown tuffaceous mudstone, 20 feet stratigraphically above top of 2-foot white tuff marker bed. Collectors: D. F. Hewett and K. E. Lohman, September 20, 1950. This locality is shown on Mr. Dibblee's map, and is near vertebrate localities Number 462 and 463.

Relative Abundance

R=rare; F=frequent; C=common

Achnanthes exigua Grunow	R
sp.	F
Cocconeis placentula Ehrenberg	R
Eunotia cf. E. alpina (Naegli) Hustedt	R
sp.	R
Fragilaria spp.**	R
Gomphonema angustatum (Kutzing) Rabenhorst	F
gracile Ehrenberg	F
lanceolatum Ehrenberg *	F
cf. G. parvulum (Kutzing) Grunow *	R
salinarum Pantocsek	R
Gomphonema subclavatum Grunow *	F
sp. aff. G. subclavatum Grunow **	R
spp.**	F
Melosira sp. aff. M. distans (Ehrenberg) Kutzing	F
sp. aff. M. italica (Ehrenberg) Kutzing **	C
spp.**	F
Navicula bacillum Ehrenberg	R
cuspidata var. ambigua (Ehrenberg) Cleve	C
dicephala (Ehrenberg) Wm. Smith *	F
sp. aff. N. exigua (Gregory) O. Muller	R
pupula var. rectangularis (Gregory) Grunow *	R
Neidium iridis (Ehrenberg) Cleve	F
Mitzschia cf. N. clausii Hantzsch	R
cf. N. Lamprocampa Hantzsch	R
spp.	F
Pinnularia borealis Ehrenberg	R
brevicostata Cleve	R
major (Kutzing) Cleve *	C
cf. P. molaris Grunow	F
spp.**	F
Stauroneis cf. S. acuta Wm. Smith	F
cf. S. anceps Ehrenberg	F
sp.**	R
Tetracyclus cf. T. ellipticus var. lancea (Ehrenberg) Hustedt	R

This diatom flora bears such a close similarity to assemblages from the middle and upper Virgin Valley beds of Barstovian age in Humboldt County, Nevada, that the beds at Black Canyon may be correlated with them with reasonable assurance. In the above list a single asterisk (*) indicates those identified species and varieties which also occur in the Virgin Valley beds. The double asterisks (**) indicate new species described in a paper on the diatoms from the Virgin Valley beds now in preparation. It is the presence of these new species, now known only from the two localities, that gives the greatest assurance to the correlation.

In the Black Canyon area, the diatoms occur with no significant change in floral composition at several horizons, beginning 20 feet above the 2-foot white tuff marker bed and extending upward through a stratigraphic thickness of about 100 feet. In no place in this area do the diatoms occur in such concentration as to justify the use of the term diatomite, although some of the pure white tuffs might be mistaken for diatomites on superficial field examination. Numerous collections made through a stratigraphic thickness of about 150 feet below Diatom locality 3492, including the 2-foot white tuff marker bed, failed to yield even a trace of diatoms.

Ecology. This diatom assemblage is made up wholly of fresh water species among which a few can today also tolerate mildly saline conditions. A fairly shallow, cool lake in which fine clastic material, including primary or reworked volcanic ash, was being introduced at varying rates would explain the uneven distributions of the diatoms. The fact that the diatom flora shows no significant change in composition in the stratigraphic interval of about 100 feet suggests that these conditions were constant for the time represented by the deposition of these beds. Marked changes in temperature, pH, or salinity are usually reflected in the diatom population.

Photo 40. Conglomeratic gray sandstone of Barstow Formation overlying basalt flow in Black Canyon.

LANE MOUNTAIN ANDESITE

Areal Distribution. At Lane Mountain, Lane Mountain quadrangle, is a large extrusive mass of andesite of late Tertiary age that rests on the eroded surface of the pre-Tertiary crystalline bedrock. This andesite was mapped and named by McCulloh * as the Lane Mountain Volcanics.

McCulloh describes this unit in the Lane Mountain area as follows:

"Cap-like remnants of fairly flat lying lava flows of calcic hornblende andesite, dacite, and quartz-bearing latite are exposed in patches scattered from the northwest corner of the area, where they rest upon the beveled plutonic rocks of Williams Plain, to the central part of the south edge of the area (Sec. 34, T. 11 N., R. 1 E.) where they rest upon tilted and eroded strata of the Pickhandle Formation. These remnants are not all parts of a single lava flow. However, they all occupy an analogous position superjacent to all the older rocks of the area. Hence, the scattered patches are correlated with each other and are described here under the heading Lane Mountain Volcanics, a name derived from the thick section of quartz-bearing latite flows which compose the mass of Lane Mountain.

"Petrology

"Four different rock types are found in the five areas of rocks of the Lane Mountain Formation, and the author concludes that these represent remnants of four separate lava flows of approximately the same age. All of the rocks contain some glass, and difficulty is consequently encountered in assigning rock names. The names have been given on the basis of feldspar composition, and presence or absence of quartz phenocrysts.

"In the northwestern corner of the area, a thin flow of hornblende-biotite dacite porphyry rests upon (Mesozoic plutonic) rocks . . . The rock is characteristically light brown to dark brown, massive, and markedly porphyritic, although a discontinuous zone of glass at the base is light gray and flow banded. Thin sections of both facies . . . indicate the following mineral compositions:

10–32%	andesine—slightly zoned from An_{38} to An_{45}.
3– 5%	quartz
3– 9%	biotite
2– 6%	hornblende (basaltic hornblende partly altered to hematite pseudomorphs)
1– 2%	accessory hematite, magnetite, apatite, and zircon
60–80%	hyaline groundmass

"The texture is hemicrystalline, porphyritic. Euhedral to subhedral plagioclase, embayed subhedral quartz, and subhedral biotite tablets are embedded in a glassy groundmass containing some microphenocrysts. The phenocrysts range up to 2 mm long, and probably average about 1 mm.

"The cores of plagioclase crystals in one specimen . . . are filled with irregular to tubular glass inclusions. Such inclusions in plagioclase are common in the Tertiary intrusive rocks to be described, as well as in some members of the Lane Mountain Volcanics. They are hereafter referred to simply as glass inclusions, a full description being reserved for the section on the feldspars of the volcanic rocks.

"At Lane Mountain a layered flow of quartz-bearing biotite latite more than 450 feet thick rests upon . . . diorite. A thin and discontinuous band of black hemicrystalline obsidian crops out at the base of the flow. A local thin section of white siliceous tuff, poorly sorted but well stratified, intervenes between the base of the obsidian and the underlying diorite.

"The latite is pink or purplish-pink, massive, resistant, thinly flow-banded, and hemicrystalline, porphyritic. Four specimens . . . have the following mineralogical compositions:

3–15%	calcic oligoclase (An_{28} to An_{35}). The feldspar of the obsidian is more calcic (An_{35} to An_{45}) and zoned.
5–11%	sanidine
1– 3%	quartz
0– 2%	biotite
60–90%	glass

"The texture is hemicrystalline, porphyritic. Euhedral phenocrysts of plagioclase and sanidine, euhedral microphenocrysts and skeleton crystals of sanidine, and rare subhedral corroded quartz crystals are embedded in a glass groundmass. The phenocrysts range up to 1 mm long.

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* McCulloh, T. H., Geology of the southern half of the Lane Mountain quadrangle, California: PhD. Thesis, University of California at Los Angeles, 1962, unpublished.

"A remnant of biotite dacite agglomerate or flow breccia, having a maximum thickness of at least 130 feet, forms a massive resistant bluff just east of Jackhammer Gap. The breccia is that of a single flow resting unconformably upon rocks of the Jackhammer and Pickhandle Formations, and upon Tertiary intrusive rocks to be described. The attitude of the basal contact indicates the remnant dips gently toward the south.

"The rock of which the flow breccia is composed is dark purple to dark red-brown dacite porphyry. A typical specimen . . . has the following composition:

15%	quartz
25%	andesine (An_{46})
5%	biotite (partly altered to hematite)
5%	hornblende (green-brown hornblende extensively altered to hematite)
50	groundmass of glass, hematite, and fine-grained feldspar.

"The texture is hemicrystalline, porphyritic. Euhedral lath-shaped and blocky phenocrysts of plagioclase, large embayed quartz phenocrysts, and highly altered euhedral biotite tablets and stubby hornblende prisms are enclosed in a groundmass of glass containing feldspar microlites and finely divided hematite.

"In the two remaining areas of Lane Mountain Volcanics, the one southeast of Pickhandle Pass, and the one in Sec. 34, T. 11 N., R. 1 E., dark red calcic hornblende andesite agglomerate rests unconformably upon rocks of the Pickhandle Formation. The unconformable relations are particularly well shown in the western one of the two areas, only a short distance east of the Barstow-Camp Irwin Road.

"A single specimen . . . is dark purplish-red, massive, and porphyritic. It is composed of:

30	labradorite (An_{65}), containing abundant glass inclusions
10	hornblende
1	biotite
1	accessory hematite and apatite
58	groundmass (glass containing finely divided hematite (?))

"Age

"The preceding paragraphs introduce the problem of the age of the Lane Mountain Volcanics. One may conclude with some certainty only that they are younger than upper Miocene.

"The impressive unconformity between the volcanics and older Tertiary rocks indicates a considerable erosion interval between upper Miocene time and the time of extrusion of Lane Mountain Volcanics, if ordinarily accepted standards of erosional rates are used.

"Since their extrusion, the Lane Mountain Volcanics were faulted and probably folded, and subsequent erosion has made such inroads that only remnants remain of flows which locally exceed 450 feet in thickness.

"Thus, the extrusion of the Lane Mountain Volcanics is crowded between a post-Barstovian period of folding and faulting followed by a time interval during which cubic miles of consolidated rocks were removed by erosion, and a post-Lane Mountain interval of sufficient length to allow for faulting and nearly complete erosional stripping of the volcanics. After consideration of these facts and assumptions concerning erosion rates, a questionable Pliocene age seems most applicable to the Lane Mountain Volcanics."

At the west edge of the Williams Plain area in eastern Opal Mountain quadrangle are two large and two small buttes of andesite similar to that of Lane Mountain; therefore they are referred to the Lane Mountain Andesite.

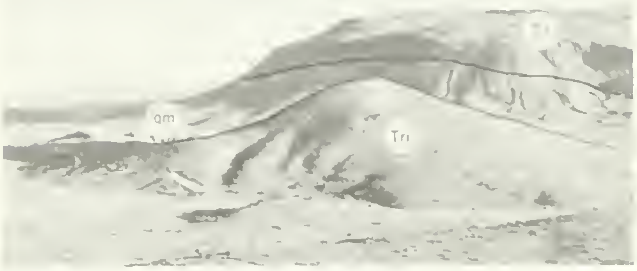

Photo 41. View southeast toward Williams Plain, showing rhyolitic plug of Opal Mountain Volcanics (Tri); Lane Mountain Andesite (Ta); and quartz monzonite (qm). Lane Mountain visible in distant left

Photo 42. View northwest on Williams Plain, showing surface of low relief cut on quartz monzonite, capped by Lane Mountain Andesite in large buttes in background.

Topographic Expression. The Lane Mountain Andesite is highly resistant to erosion and forms a protective capping on the less resistant quartz monzonite on which it rests. The andesite weathers to large angular blocks which accumulate as talus that largely conceals the underlying quartz monzonite under the steep slopes and bluffs surrounding the buttes.

Relations to Other Rocks. On each of the two buttes the andesite has a flat base where it rests on quartz monzonite, and has a slightly domed top surface, suggesting the lava to be thicker at the center of each butte than at its marginal bluffs. The andesite is about 480 feet thick on the southern butte; about 340 feet on the northern one.

Lithology. The Lane Mountain Andesite exposed in the Opal Mountain quadrangle is a massive brown to gray porphyritic rock with a dense aphanitic to vitreous groundmass. Phenocrysts make up 25 to 50 percent of the rock and include, in decreasing abundance: plagioclase (andesine), basaltic hornblende, and biotite. The plagioclase occurs as clear white rectangular phenocrysts from 1 to 3 millimeters long and about half as wide. The hornblende is in the form of small black prismatic phenocrysts 1 to 2 millimeters long. The biotite occurs as small hexagonal flakes less than 1 millimeter across. The groundmass consists of glass, partly devitrified, with a refractive index of about 1.50. It contains small lath-like crystals of plagioclase.

Origin and Emplacement. The two exposures of the Lane Mountain Andesite at the western edge of the Williams Plain are either erosional remnants of an extensive flow that may have once covered this plain, or are local extrusions that covered areas only slightly greater than they do now. The latter origin is believed more probable, because no other erosional remnants of this resistant rock are seen on the Williams Plain within the Opal Mountain quadrangle, nor are any feeder dikes.

If the two isolated masses of the Lane Mountain Andesite are local extrusions, each probably issued from a vent now concealed beneath it and spread out as a viscous magma on the beveled surface of quartz monzonite. This origin is suggested by the lack of exposed fissure dikes of this rock under each andesite capping, the nearly circular outline of each andesite exposure, and by the slightly domed top surface of the larger butte—all of which suggest that the andesite issued as a viscous lava from a vent concealed directly under it and built up as a low volcanic pile.

Age and Correlation. The age of the Lane Mountain Andesite is uncertain, but available evidence corroborates McCulloh's conclusion that it is probably very late Tertiary, probably Pliocene. The andesite is much younger than the granitic rocks upon which it rests, and is younger than the rhyolitic rocks of the Opal Mountain(?) Volcanics, as indicated in the northern butte where the andesite rests in part on one of these rhyolitic plugs.

The nearly flat, beveled, erosion surface of the pre-Tertiary crystalline rocks upon which the Lane Mountain Andesite rests must have been cut long after deposition and deformation of the Pickhandle and Barstow Formations of the Mud Hills section. The long interval during which these formations were stripped off of the Williams Plain area, if they ever were deposited there, must have occurred throughout much of late Tertiary or Pliocene time, so that the Lane Mountain Andesite is almost certainly not older than Pliocene and is more likely of late Pliocene age.

The Lane Mountain Andesite is no doubt older than the Black Mountain Basalt of Pleistocene age because the andesite occurs as erosional remnants that stand several hundred feet higher than the valley surface on which the basalt was extruded. Also the original flow surface of the andesite is largely if not entirely destroyed by erosion, while that of the basalt is still largely preserved, even where it is deformed. In other words, an early mature erosion surface is cut on the andesite, whereas the erosion surface on the basalt is still in the early youthful stage of the erosion cycle. These conditions indicate that the andesite was extruded, elevated several hundred feet, and eroded, before the basalt was poured out onto a lower valley surface, thus placing the upper age limit of the Lane Mountain Andesite as Pleistocene.

Photo 43. View northeast over Harper Valley, showing steep southwest front of Black Mountain in background.

Quaternary Rocks

BLACK MOUNTAIN BASALT

Usage of Name. The basalt flow that covers the Black Mountain south of Indian Wells Valley, Saltdale quadrangle, was first described and named the Black Mountain Basalt by Baker (1912, p. 117–142). This flow was later described by Hulin (1925, p. 20–61) as unconformably overlying Tertiary sediments, and of probable very late Tertiary or early Pleistocene age. It was still later described and mapped by the writer (Dibblee, 1952, p. 30, pl. 1) who found that it lies unconformably on the Ricardo Formation (Pliocene), is slightly deformed, and is not overlain by any other formation; it was thereby concluded to be of probable Pleistocene age.

By coincidence the Black Mountain in the Opal Mountain quadrangle is likewise covered by a basalt flow of probable Pleistocene age. Here, the basalt lies unconformably on strongly deformed strata, of Miocene age, and is itself locally deformed and elevated. This flow is referred to as the Black Mountain Basalt not only because it covers Black Mountain and vicinity in the Opal Mountain quadrangle, but because it was probably extruded at nearly the same time as the Black Mountain Basalt in the Saltdale quadrangle, and is of similar lithology.

Areal Distribution. The Black Mountain Basalt is exposed extensively in the Opal Mountain quadrangle, in the form of two large and several small extrusions, probably all contemporaneous. The largest of these is an extensive lava sheet that covers Black Mountain and extends west across the mouth of Black Canyon, to cover an area of some 28 square miles. From this large exposure the Black Mountain Basalt extends, concealed, southward and southeastward for an unknown distance under the alluvium of Harper Valley, where three out of four test holes drilled on and near Harper Dry Lake passed through it. The concealed southeastward extension may connect with the outcrops of basalt 10 miles east of Harper Dry Lake and the exposure at the west end of the Mud Hills.

The other large sheet of the Black Mountain Basalt covers northeast Black Mountain for some 20 square miles. Small isolated outcrops of the Black Mountain Basalt occur along the Blackwater fault in the extreme northwest portion of the Opal Mountain quadrangle.

Topographic Expression. The Black Mountain Basalt is more resistant to erosion than any other formation within the mapped area. Its resistance is so great that even where the lava is elevated high above the valley areas it is, in most places, hardly dissected. Where the basalt is not severely deformed and is un-

Photo 44. View north across east fork of Black Canyon, showing dissected flow of Black Mountain Basalt capping beveled surface of white tuff of Pickhandle Formation. Pilot Knob visible in distant left.

dissected it forms smooth topography, as seen from a distance. However, it everywhere breaks into large angular blocks that form a surface that is extremely rough on closer view. On steep slopes or where the basalt flow is eroded through, angular blocks that break off from the hard lava sheet accumulate downslope as talus which masks the underlying formation. On the southeast slope of Black Canyon the basalt flow has slumped down over the underlying Tertiary sediments to form numerous landslides and talus slopes.

Thickness and Stratigraphic Relations. On the southwestern margin of Black Mountain, the Black Mountain Basalt is composed of several flows that may total 100 feet or more, but northeastward it thins to an extensive sheet 30 feet or less thick. The basalt flow lies unconformably on the beveled surface of tilted beds of the Pickhandle and Barstow Formations. No formation overlies the Black Mountain Basalt, although in Harper Valley it is overlain by a thin veneer of Recent alluvium.

On northeast Black Mountain the basalt is about the same thickness as on Black Mountain proper, and thins northeastward in the same manner. The east edge of this basalt flow wedges out into Quaternary gravel. The basalt rests unconformably on soft volcanic gravels of the Barstow Formation. There is no superjacent formation.

In Harper Valley three of four test holes drilled on and near Harper Dry Lake encountered from 142 to 183 feet of basalt, supposedly the Black Mountain Basalt, below Quaternary alluvium. None was encountered in the most southwesterly hole, which passed from alluvium into gneiss.

Photo 45. Dip slope of Black Mountain Basalt flow overlying Barstow Formation (covered by basalt talus at right). View northwest from mouth of Black Canyon.

Photo 46. Exposure of several flows of Black Mountain Basalt near mouth of Black Canyon.

Lithology. The Black Mountain Basalt is a hard, black, fine-grained, diabasic-textured rock. It is massive and invariably vesicular, with some flows containing numerous vesicles and others containing few. It is composed of the following minerals in decreasing order of abundance: plagioclase (labradorite), augite, an unidentified opaque mineral, and hematite.

Conditions of Deposition. The large areal extent of the Black Mountain Basalt flow at Black Mountain, and its thinness indicates that it was extruded as fluid lava that spread out over large areas of the desert floor. It was extruded from fissure vents now concealed presumably beneath its thickest parts, possibly along the Black Mountain and Blackwater fault zones.

The surface upon which the Black Mountain Basalt sheets were poured—both at Black Mountain, and northeast Black Mountain—must have been a nearly level plain, apparently a pediment cut on pre-Tertiary granitic rocks and deformed Tertiary strata. The Tertiary volcanic rocks of the Opal Mountain and Williams Plain areas protruded above this plain as hills around which the basalt flowed. Portions of these two extensive basalt sheets were later elevated and tilted by movements along the Harper Valley and Blackwater fault zones, to form the present tilted tablelands of Black Mountain and Northeast Black Mountain. These mountains are therefore of tectonic and not of direct volcanic origin, as has generally been believed.

Age and Correlation. The Black Mountain Basalt is younger than the Miocene Pickhandle and Barstow Formations on which it rests unconformably. It is probably younger than the Lane Mountain Andesite of Pliocene(?) age, because the basalt rests on an erosion surface several hundred feet lower and younger than that on which the andesite rests. Therefore, the basalt must be Quaternary in age. This age is confirmed by the outward lensing of the basalt into Quaternary gravel at the east margin of the northeast Black Mountain mesa.

Photo 47. Black Mountain Basalt, showing two vesicular flows at top and bottom, separated by a massive flow at center. Near mouth of Black Canyon.

OLDER ALLUVIUM

General Features. The weakly consolidated older alluvium, of probable Pleistocene age, underlies much of the slightly elevated area both west and east of Harper Valley; it also underlies Recent alluvium in both Harper and Superior Valleys. The older alluvium is probably several hundred feet thick under Harper Valley, and in the elevated areas to the east and west it is as thick as 200 feet. Throughout the mapped area, it rests on a beveled erosion surface on the Tertiary and pre-Tertiary rocks; its top surface is a deposition surface that is dissected in the elevated areas. It is deformed only locally, and there only by slight tilt of fault blocks. The older alluvium is an extensive older valley fill, derived from highland areas within and near the mapped area.

The older alluvium is composed of irregularly bedded light-gray gravel and sand. This detritus consists mainly of granitic and metamorphic rocks but in places it contains minor amounts of Tertiary volcanic and sedimentary rocks. In most places the basal part is composed of cobble gravel, whereas the upper part is mainly granitic sand.

The older alluvium exposed west of Harper Valley is composed almost entirely of granitic detritus. Southwest of the Lockhart fault it is more than 200 feet thick, with the base unexposed. Northward from this fault it forms a thin veneer on pre-Tertiary rocks, extending up the southwestern pediment surface of the Fremont Peak range. On the east side of Harper Valley, from the Mud Hills northwesterly, the older alluvium is as thick as 300 feet. It is slightly deformed, mostly by southwestward tilt. In the Mud Hills it rests on the beveled surface of the synclinally folded Barstow Formation. Northward it fills floodplains of canyons eroded into the Pickhandle and Jackhammer Formations and quartz monzonite.

In the vicinity of Opal Mountain, a local thin covering of older alluvium as much as 50 feet thick composed of cobble-gravel, is derived from the Opal Mountain Volcanics. The alluvial gravel is dissected and rests on the Opal Mountain Volcanics, Pickhandle tuff, and Black Mountain Basalt.

Under Harper Valley the older alluvium is concealed under Recent alluvium, from which it is undifferentiated in wells. Several wells drilled in and near Harper Dry Lake pass from older alluvium into the Black Mountain Basalt at depths ranging from 384 to 487 feet. In southwestern Harper Valley numerous water wells have been drilled, some deeper than 500 feet, but none are known to have reached the base of the Quaternary alluvium. In this area, the older alluvium is presumably underlain by the pre-Tertiary crystalline rocks that crop out to the west.

Conditions of Deposition. The older alluvium appears to have been deposited in Pleistocene time after an interval of diastrophism and erosion that affected probably all the mapped area with the possible exception of part of Harper Valley. Much of this erosion surface, which was probably of high relief, became reduced to a pediment sloping towards what is now Harper Valley. The older alluvium was derived from erosion of highland areas that persisted throughout Quaternary time, and accumulated in Harper Valley and over much of the surrounding pediment surface. Some of these highland source areas were the Fremont Peak range, Slocum Mountain, Williams Plain, and the Waterman Hills. During deposition of the older alluvium the Black Mountain Basalt was extruded and flowed out over the pedimented surface cut on the Tertiary rocks of the area that is now Black Mountain and northeast Black Mountain.

Terrace Gravels. Slightly elevated and dissected alluvial gravels form terraces in canyons in many parts of the mapped area, chiefly in the Gravel Hills and the Mud Hills. The largest deposit forms a low mesa on the northwest side of Black Canyon. These deposits are fillings of former flood plains of the canyons, hence are locally derived. The gravels, which are rarely over 20 feet thick, are mapped as part of the older alluvium but must be younger than most of it because in the Mud Hills they are at lower elevations and are undeformed. Some of the slightly dissected large alluvial fans on the east side of the Fremont Peak range may have been deposited contemporaneously with the terrace gravels of the Gravel Hills and Mud Hills.

SURFICIAL SEDIMENTS

Areal Distribution and Facies. Undissected, unconsolidated alluvium of Recent and very late Pleistocene age fill all the valleys within the map area and the flood plains of all canyons that emerge from the adjoining hills and mountains. The most extensive deposits of alluvium cover Harper Valley and Superior Valley. Four facies of surficial sediments are recognized, all of which grade into each other. These are 1) fan alluvium; 2) valley alluvium; 3) playa clay; and 4) wind-blown sand. On plate 1 the first two facies are mapped as alluvium (Qa), as these two facies grade into each other over such broad areas that they are undifferentiable. The playa clay is shown as Qc. Deposits of wind-blown sand in various parts of Harper Valley are shown as Qs.

Fan Alluvium. The fan alluvium is coarse, unsorted fanglomerate deposited along the bases of the mountains and hills. The most extensive deposit forms a piedmont alluvial fan along the northeastern margin of the Fremont Peak range. It is composed of unsorted angular clasts as large as eight feet in longest dimension. This coarse fan alluvium extends far up the re-entrants and canyons on this flank of the range to elevations as high as 2,800 feet. The southwest margins of the Gravel Hills and the Mud Hills are flanked by fan alluvium composed mainly of gravel of granitic detritus. Along the steep southwestern bases of Black Mountain and northeast Black Mountain are small black fans derived from the Black Mountain Basalt.

Valley Alluvium. The valley alluvium is the outwash, medium-grained facies of the alluvium that fills the greater, nearly level portions of Harper, Cuddeback, and Superior Valleys. It consists mainly of tan to light gray, loose to slightly indurated, bedded, granitic sand with some granitic pebble-gravel and silt. The slope of its undissected surface ranges from 100 to about 5 feet per mile.

Although many wells have been drilled into the valley alluvium of Harper Valley, the thickness is not definitely known because in wells the unconsolidated alluvium is not readily differentiable from the older alluvium, which has the same general lithology. However the Recent Valley alluvium is probably not more than 100 feet thick.

Playa Clay. The playa clay is the playa or dry-lake facies of the alluvium, and consists of light tan-gray argillaceous clay and fine micaceous silt. It covers the surface of Harper Dry Lake, the small playas east of Fremont Peak, Cuddeback Dry Lake, and the small dry lakes in Superior Valley. In the larger playas, such as Harper and Cuddeback Dry Lakes, the clays contain alkali carbonates and chlorides that form a thin white crust a centimeter or less thick after evaporation of rainwater that occasionally collects there.

The surface of the playa alluvium is level; its thickness is roughly 100 feet in Harper Lake, as indicated in three test holes drilled there, and about 90 feet in one of the playas in Superior Valley, as indicated in a water well.

Windblown Sand. Loose windblown sand has been banked against the western bases of practically all the hills on the east side of Harper Valley by the frequent westerly gales. The largest sand deposits are those along the southwestern base of Black Mountain ridge northeast of Harper Dry Lake where they are banked high against the basaltic outcrops of Black Mountain. Streamers of sand extend over the top of the southern part of the ridge and down its leeward east flank. A moderate thickness of windblown sand overlies the older alluvium along the southwestern base of the Mud Hills. Other deposits of windblown sand are banked on the western base of the granitic exposures of the Waterman Hills, and against the western bases of the low isolated hills 1 to 2 miles west in Harper Valley.

Along the eastern and southeastern margins of Harper Dry Lake are deposits of windblown sand, mostly in the form of small dunes. This sand apparently accumulated as it was blown across the dry lake and adhered to the damp ground along the eastern margin of the playa.

The windblown sand is light buff, fine-grained, and well sorted. The grains, subrounded, are almost entirely quartz and feldspar.

STRUCTURE

Regional Setting

The Fremont Peak and Opal Mountain quadrangles are in the west central part of the Mojave Desert geomorphic province, which is bounded on the north and southwest by the Garlock and San Andreas faults, respectively. The pre-Tertiary crystalline basement complex, exposed and partly buried by Cenozoic formations throughout this region, is a granitic batholith believed to be continuous with that of the Sierra Nevada to the northwest. It contains roof pendants of metamorphic rocks. The basement complex was stabilized during the Nevadan orogeny into a rigid or semi-rigid mass that in this area is free from widespread fracturing and shearing. It yielded to Cenozoic diastrophic stresses by broad warping, and by faulting.

During Cenozoic diastrophism the surface of the crystalline basement complex was apparently compressed into several broad upwarps and downwarps, generally along axes trending east-west, although a few vary from this trend as much as 30 either way. This diastrophism was more or less continuous during Cenozoic time, when the upwarping areas were undergoing erosion, and the eroded detritus, along with the material from contemporaneously active volcanic eruptions, was accumulating in the downwarping areas. Compared to the underlying crystalline basement complex, the Cenozoic formations are relatively plastic and yielded to continuing stress by folding and faulting.

One of the large basins of deposition of the Mojave Desert province lies partly within the two mapped quadrangles. This is a trough-like downwarp filled with strata of the Jackhammer, Pickhandle, and Barstow Formations to a maximum depth of about 6,000 feet. This depositional basin is here referred to as the Barstow basin (mentioned as "Barstow trough" by Bowen, 1954, p. 81), because it is filled mainly with sediments of the Barstow Formation. The areal extent and evolution of this basin has been recounted in the sections on deposition of the Pickhandle and Barstow Formations. During deposition of the Barstow Formation, this basin became well defined and extended from the south end of Cuddeback Valley southeastward through the Gravel Hills, Black Mountain, northeastern Harper Valley, Mud Hills, and through the Calico Mountains and the valley area to the south and east.

The center of the mapped area is about 27 miles south of the Garlock fault and about 57 miles northeast of the San Andreas fault. These bounding faults of the Mojave Desert province are described by Hill and Dibblee (1953) and in many other publications. Within this province neither large thrust faults like those mapped farther east by Hewett (1956, p. 50–61), nor great north-trending normal faults like those of the Basin and Range province to the north are recognizable. Nearly all the major faults or fault zones within the Mojave Desert province are vertical or steep, and most of these trend northwesterly, parallel to the San Andreas. Many are known to have been active in Quaternary time because they affect Pleistocene formations or Recent alluvium. Evidence of right-lateral movement has been noted on some that trend

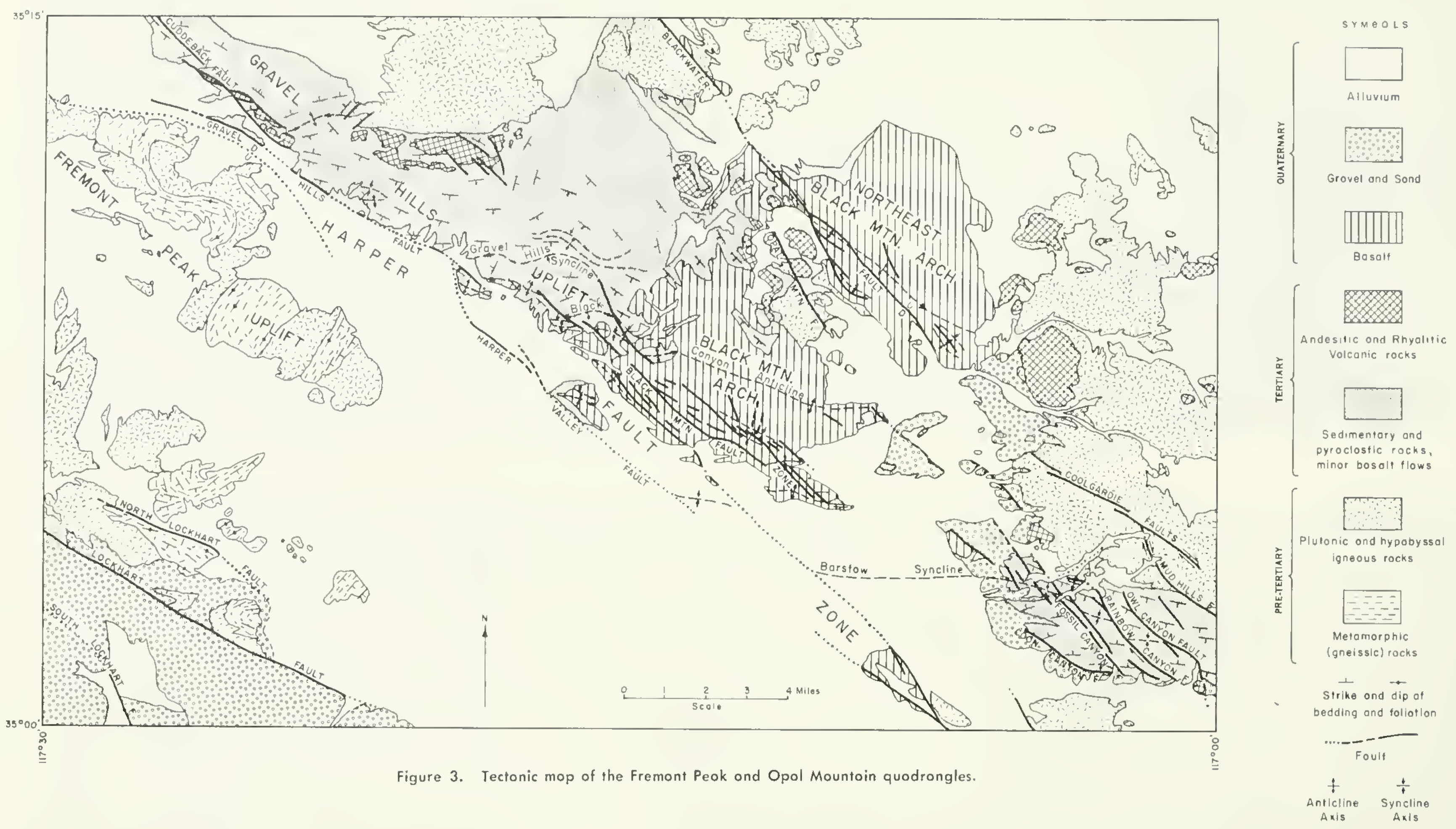

Figure 3. Tectonic map of the Fremont Peak and Opal Mountain quadrangles.

northwest. The northwest-trending fault zones appear to have formed independently of structural trends of the metamorphic rocks of the basement complex.

Three major northwest-trending faults or fault zones pass through the mapped area: the Blackwater-Mud Hills fault zone, the Harper fault zone, and the Lockhart fault zone. Most of the mapped faults occur along or near these three major fault zones. The first two zones diagonally transect the Barstow basin, and the Cenozoic formations in the block they bound are much deformed, mostly by folding along east-trending axes. The adjacent blocks, on which the basement complex is exposed, have been more stable.

Structure of Pre-Tertiary Basement Complex

The structure of the pre-Tertiary basement complex has already been described under Rock Units. The plutonic igneous rocks are all massive or nearly so. The regional attitude of the metamorphic rocks of the Waterman Gneissic Complex west of Harper Valley is generally N. 60° E. with vertical or steep southeasterly dips. This regional attitude conforms to that of the metamorphic rocks exposed south of the mapped area in the hills south, west, and east of Hinkley and in the hills north of Barstow.

Area West of Harper Valley

The Fremont Peak Range and the low hills to the south expose only the basement complex and constitute the elevated portion of the stable block southwest of the Harper fault zone. The northwest-trending range that includes Fremont Peak is a semimountainous exposure of basement complex, cut by numerous dikes of quartz latite that trend generally east-west. The topogtaphy of the Fremont Peak range, with its locally precipitous northeastern slope and gentle, partly alluvium-covered, southwestern slope, strongly suggests uplift on a possible buried fault along its northeastern base, and tilting to the southwest. Any scarp that may have formed by movement on such a fault has long since been eroded and destroyed, and its trace concealed by alluvium.

In the area southwest of the Lockhart fault, the older alluvium is underlain by Tertiary sedimentary rocks, as is indicated in several test holes. A test hole drilled in Sec. 11, T. 10 N., R. 5 W., 5 miles southwest of Lockhart Ranch, encountered Tertiary shale and sandstone below the alluvium, then drilled through granite from 2,640 feet to bottom at 3,064 feet (Bowen, 1954, p. 182). Also, southward-dipping Tertiary shale and sandstone crop out in Secs. 15 and 16, T. 11 N., R. 6 W., on the south side of the South Lockhart fault just west of the mapped area. Three test holes drilled in Secs. 22, 26, and 35 of T. 11 N., R. 6 W. passed from older alluvium into Tertiary sedimentary rocks (see logs herein).

Lockhart Faults. The Lockhart group of faults includes the Lockhart fault, the North Lockhart fault, and the South Lockhart fault. The principal fault of the group, the Lockhart fault, is found 3 miles southwest of the Lockhart ranch, after which it was named. The fault trace is not exposed and is difficult to recognize on the ground, but it appears prominently on aerial photographs as a straight line running N. 50° W. for about 10 miles within the Fremont Peak quadrangle and for another 15 miles west of it. It separates the area of low hills exposing the basement complex on the northeast from the higher desert plain underlain by older alluvium on the southwest. The fault dies out southeastward into Quaternary alluvium. It is known to have been active in very late Quaternary time because it breaks the older alluvium. The presence of exposures of basement complex only on the northeastern block suggests this is the upthrown block; yet the southwestern block is topographically higher, suggesting it was the upthrown block in the latest movements. These relative vertical displacements may be only apparent, and the real displacements may be lateral. Indeed, recent mapping in the Boron quadrangle (Dibblee 1959) reveals evidence suggestive of right-lateral movement on the Lockhart fault. The 25-mile extent of the Lockhart fault indicates it to be a major fault, but the total displacement is unknown.

The North Lockhart fault is a mile and a half northeast of the Lockhart fault and parallels it for about 4 miles. Evidence of this fault is (1) a low northeast-facing scarp separating the basement complex on the southwest from Quaternary alluvium on the northeast and (2) a marked difference in strike of the metamorphic rocks on opposite sides of the fault. The block on the southwest side of the fault has been elevated, as indicated by its northeast-facing scarp. Small right-lateral displacement in the basement complex is suggested by possible southeastward offset of the northeast-striking Waterman Gneissic Complex (exposed in Sec. 14, T. 11 N., R. 5 W.) from its possible counterpart southwest of the fault.

The South Lockhart fault lies 2 to 3 miles southwest of the Lockhart fault and transects the southwestern corner of the Fremont Peak quadrangle. Northwest of the quadrangle it approaches and probably joins the Lockhart fault. To the southeast it diverges from it and dies out in older alluvium. The fault is within older alluvium and its position is marked by the weak scarps in this formation which show on aerial photographs. Just west of the quadrangle Tertiary sedimentary rocks crop out on the south side of the fault, and a low northeast-facing scarp cuts the older alluvium. At the southern border of the quadrangle the scarp in the older alluvium reverses and faces southwest, and south of the border the older alluvium east of the fault is slightly arched into an east-plunging anticlinal structure, beyond which the fault dies out. These relationships suggest right-lateral movement of small displacement on this fault.

Harper Valley Area

Harper Valley, which occupies much of the southern part of the mapped area, is the relatively depressed, alluvium-filled portion of the large block southwest of the Harper fault system. Test holes and water wells drilled in it indicate that Quaternary alluvium fills it to a depth of about 450 feet. In the southwestern part of the valley the alluvium is probably underlain by rocks of the basement complex. These crop out in the hills west of the valley, in isolated hills just southeast of Harper Dry Lake, and were encountered at 460 feet in Harper test hole No. 1 in southwestern Harper Dry Lake.

The two other test holes in Harper Dry Lake, Harper No. 4 and 5, encountered a few hundred feet of the Barstow(?) Formation, then the basement complex below Quaternary alluvium and basalt. Harper No. 2, east of Harper Dry Lake, encountered the Barstow Formation below Quaternary alluvium and basalt, and bottomed in this formation at 1,117 feet.

These test holes, together with the thick section of the Barstow Formation exposed north and east of Harper Valley, indicate that in the northeastern part of Harper Valley the Quaternary alluvium is underlain by the Barstow Formation, and that this formation thickens northeastward toward the axis of the former Barstow basin. That the Barstow Formation encountered in these test holes is probably flat-lying and undeformed, is indicated by the fact that the basalt flow in it was encountered at about the same depth in two of these holes.

The axis of the former Barstow basin or the line of maximum original thickness of the Tertiary formations deposited in it, probably occurs along the southwestern base of the Gravel Hills-Black Mountain uplift (northeastern edge of Harper Valley) then trends eastward through this valley to the axis of the Barstow syncline in the Mud Hills. The axis of the Barstow syncline does not necessarily follow the axis of the Barstow basin, although east of the Harper fault zone it probably does.

The results of a gravity geophysical survey by the U. S. Geological Survey (Mabey, 1960) in Harper Valley indicate that the axis of the Barstow syncline extends from the Mud Hills west to the probable southeastern extension of the Black Mountain fault group. The position of this synclinal axis west of this fault group is not clear, but the gravity results suggest that the axis is offset to the northwest about a mile on the Black Mountain fault, rises westerly, and disappears. The gravity results also suggest the northeastern block of the Black Mountain fault to be relatively depressed where the fault transects the Barstow syncline, but this may be due to right-lateral displacement on this fault.

Harper Fault Zone. The Harper fault, named by Hewett (1954), is really a northwest-trending zone of discontinuous, parallel, high-angle faults along the southwest margin of the Gravel Hills and Black Mountain. This fault zone apparently dies out at the north border of the mapped area, but presumably continues southeast of the mapped area along the straight southwest base of the Waterman Hills north of Barstow, where it was mapped as the Waterman thrust by Bowen (1954, p. 104, pl. 1).

The Harper fault zone is very similar to the Blackwater-Mud Hills fault zone to the northeast; the faults of both zones are vertical or steep and trend northwest. Pleistocene rocks are involved in the faulting, indicating that many were active in late Pleistocene time. Several faults even involve Recent alluvium.

The Gravel Hills-Black Mountain uplift was elevated on the Harper fault zone so that vertical displacements in the whole zone, and on most of its member faults, resulted in upthrown sides on the northeast. However, some vertical faults show upthrown sides to the southwest and reversals of displacement can be demonstrated on a few. Vertical displacements generally do not exceed 1,000 feet along any one fault. The maximum overall displacement on the Harper fault zone is about equal to the height of Black Mountain above Harper Valley, which is about 2,000 feet. Right-lateral displacements on several faults of this zone, as indicated by offsets of axes of the Black Canyon anticline and the Gravel Hills syncline, may be as much as half a mile. The overall right-lateral displacement on the Harper fault zone is probably not more than 2 miles.

Gravel Hills, Opal Mountain, and Black Mountain Areas

The Gravel Hills and Black Mountain together form an area uplifted between the Blackwater and Harper Valley fault zones. This unstable block exposes the basement complex and the overlying Tertiary and Quaternary formations deposited in the Barstow basin. These formations are moderately deformed, and this block appears to have been elevated by being squeezed between the two adjacent more stable blocks, with the maximum uplift on the Harper fault zone side.

Structure of Gravel Hills-Opal Mountain Area. The Pickhandle Formation exposed in the north central part of the Gravel Hills and in the upper Black Canyon-Opal Mountain area, dips southerly and southwesterly, respectively, off the basement complex. Between these exposures it is overlapped from south to north by the Barstow Formation, which becomes nearly flat-lying as it thins northward. Southward and westward, toward and adjacent to the northwest-bending Harper fault zone, the Barstow Formation is compressed into several folds with axes trending east-west. The largest of these folds are the domed anticline here referred to as the Black Canyon anticline, at lower Black Canyon; the large syncline, here referred to as the Gravel Hills syncline, in the southern part of the Gravel Hills; and the anticlinal saddle in the western part of the Gravel Hills.

The east-trending folds in the Barstow Formation are most tightly compressed near or between faults of the Harper fault zone; they appear to have been formed by right-lateral drag movement on that fault zone. The axes of the Black Canyon anticline and Gravel Hills syncline are offset by right-lateral displacements on several of these faults.

Structure of Black Mountain. Although the lava sheet of Black Mountain lies on the beveled surface of deformed Tertiary formations, it is deformed also by tectonic movements, though to a lesser degree. This lava sheet is so resistant to erosion that the topography of Black Mountain where covered by this lava is, with the exception of landslides, a near-perfect expression of the tectonic structure of the Black Mountain uplift since the lava was poured out over a flat surface. The lava sheet appears to have reacted to stress as a hard crust on the more pliable sedimentary strata of the underlying Barstow Formation.

Where the Black Mountain basalt sheet lies across the offset east end of the Gravel Hills syncline and Black Canyon anticline east of lower Black Canyon, it is practically undeformed except for slight eastward tilt. However, to the south and southeast the lava sheet is arched and increasingly deformed adjacent to the Black Mountain fault group.

The once flat-lying Quaternary basalt sheet of this mountain has been deformed into a compound anticlinal arch here referred to as the Black Mountain arch, plunging eastward and southeastward. It had a steep, much buckled, and faulted southwestern flank, and a gently tilted eastern flank that forms a broad tableland sloping about 2° eastward from the axis of maximum uplift. On the long eastern spur the lava sheet is gently deformed into a broad arch plunging eastward from the Black Canyon anticline. On the southeastern spur of the Black Mountain arch are superimposed several minor folds with east-trending axes.

The Harper fault zone is made up of four main faults or fault groups, which are either aligned with or parallel to each other. They are, from the northwest, Cuddeback fault group; Gravel Hills fault; Harper Valley fault; and Black Mountain fault group.

Superior Valley and Vicinity

Superior Valley is the depressed portion of the stable block of basement complex bounded on the southwest by the Blackwater fault zone and the faults in the Mud Hills. The western part of this block appears to have been elevated by movement along the Blackwater fault, and tilted eastward. The elevated part of this block exposes the basement complex in the low hills to the west, and forms the northeast-sloping basalt-covered tableland of northeast Black Mountain.

Superior Valley. The old eroded surface of the basement complex of Williams Plain slopes very gently northward under Quaternary alluvium that fills Superior Valley. The basement complex of the Slocum Mountains to the west likewise slopes eastward into the valley. The Quaternary alluvium under the part of Superior Valley within the Opal Mountain quadrangle is probably underlain by the basement complex at a maximum depth of several hundred feet.

Blackwater Fault Zone. The Blackwater fault, named by Hewett (1954) after Blackwater Well in the Cuddeback Lake quadrangle, is a major northwest-trending fault passing through the northwest corner of Opal Mountain quadrangle. The fault is traceable by its straight and prominent northeast-facing scarp for at least 11 miles northwest of that corner. Within Opal Mountain quadrangle this break is traceable as a single fault for 7 miles, then splits southeastward into a zone of several branches and disappears into the anticlinal bulge of northeast Black Mountain. Movement on this fault is inconsistent, being up on the southwest beyond and near the northwest corner of the quadrangle, with several local reversals where crossed by Slocum Wash draining into Black Canyon, and mainly up on the northeast block in the northeast Black Mountain uplift. This reversal of vertical movement is due either to "scissoring" on this fault where crossed by Slocum Wash, or to possible right-lateral movement on the fault, in which case the vertical movements would be largely apparent. Right-lateral movement on this fault, possibly as much as a mile, is suggested by the offsetting of the quartz monzonite exposures north of Slocum Wash and the Black Mountain Basalt exposures south of it, and by the offsetting of the wash itself from its normal southwestward course. The arching of the lava sheet of northeast Black Mountain between branches of this fault also suggests lateral shearing movement on the zone, as this arching cannot be explained by vertical movements alone.

Northeast Black Mountain. The thin lava sheet of the Black Mountain Basalt rests at least in part on a thin mantle of volcanic gravels of the Barstow(?) Formation, which in turn supposedly rests on the basement complex. Like Black Mountain proper, northeast Black Mountain was formed by uplift on the Blackwater fault zone along which the lava sheet was arched into an anticline. This anticline has a steep narrow southwest flank adjacent to the fault zone, and a very broad northeast flank on which the lava sheet slopes 2° eastward to form a gently inclined tableland that is very similar to that of Black Mountain proper. Between the two main branches of the Blackwater fault the lava sheet is compressed into a domed anticline, and against the east branch of this fault, as it dies out, the lava sheet is arched into another subsidiary anticline plunging southeast.

Vertical displacements on the Blackwater fault zone are small; northwest of Slocum Wash they were so slight that the fault was recognized only from aerial photographs. At northeast Black Mountain, the maximum displacement is the height of this tableland above the valley to the southwest, about 1,000 feet.

The Blackwater fault zone is aligned with the Coolgardie-Mud Hills fault zone to the southeast. The three-mile gap between these two zones is covered by Quaternary alluvium, which possibly conceals faults that connect the Blackwater and Coolgardie-Mud Hills fault zones. The attitudes and probable displacements on the faults of both zones are similar, indicating both resulted from the same stress. The many northwest-trending faults of the Mud Hills, which have similar attitudes and displacements, are also probably genetically related to the Blackwater fault zone. This zone of faulting continues southeastward along the southwest front of the Calico Mountains as recently mapped by McCulloh*, marking a major line of weakness.

Williams Plain-Mud Hills Area

Williams Plain. The plateau of Williams Plain was elevated, probably in part by movement along the Mud Hills fault and the other faults in the Mud Hills, and in part by arching on an east-trending axis just north of the Mud Hills. These movements are indicated by the southerly dip of the Tertiary formations that overlie the plutonic basement in the Mud Hills.

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* McCulloh, T. H., Geology and Mineral Resources of the Lane Mountain and north half of the Daggett quadrangles, California; U. S. Geol. Survey, unpublished map and manuscript.

Structure of the Mud Hills. In the Mud Hills the Tertiary formations are compressed or downwarped into the superbly exposed Barstow syncline, with an axis trending slightly north of west. The syncline shows indication of plunge only at its westerly exposure, where it plunges gently west toward Harper Valley. The north flank is completely exposed; the south flank only partly so. Strata on both flanks are tilted to an average dip of about 25°, but adjacent to faults are tilted as much as 75°.

Faults in the Williams Plain-Mud Hills Area. The southwestern margins of the Williams Plain and the Mud Hills are cut by a number of northwest-trending, high-angle faults within a strip roughly 3 miles wide. These may be grouped into five zones, from the northeast: Coolgardie-Mud Hills fault zone; Owl Canyon fault zone; Rainbow Canyon fault zone; Fossil Canyon fault zone; and Coon Canyon fault. All these faults are practically vertical unless otherwise indicated on the geologic map; several form small scarps in the older alluvium. Vertical displacements, none more than 1,000 feet, are variable and inconsistent. However, on most of the northeastern faults the upthrown block is on the northeast, whereas on the southwestern faults the upthrown block is on the southwest (except on the Coon Canyon fault along the southwest boundary at the Mud Hills). Several faults offset contacts and the axis of the Barstow syncline, indicating right-lateral displacement. At several places where faults are well exposed, grooves in the fault surface are nearly horizontal, indicating lateral slip. Most of these faults die out near the axis of the Barstow syncline, several into steeply tilted beds near the axis, apparently as the result of lateral drag movement. This whole complex of parallel high-angle faults appears to be a zone of right-lateral shearing, with the Tertiary formations compressed into a synclinal structure along an axis oblique to it.

Tectonic Implications

In conclusion: The structural features in the mapped area form a fairly well defined strain pattern that is generally consistent with that found throughout the rest of the Mojave Desert.

The strain pattern within the mapped area is as follows:

1. Rigid or semirigid pre-Tertiary crystalline basement complex, free from widespread shearing or fracturing.
2. The Barstow basin, a trough-like depression of the basement surface with an axis trending west-northwest across the mapped area and filled with pliable stratified rocks of Cenozoic age to a depth of 6,000 feet or more.
3. Folds in Cenozoic stratified rocks of the Barstow basin with axes trending generally east-west, more strongly compressed adjacent to major fault zones.
4. Steep, northwest-trending faults, most numerous along or near three major zones, of which two zones transect the Barstow basin.

The manner in which the Barstow basin was formed on this basement surface is a disputed problem. That it was formed as a downwarp of the basement surface and not as a fault graben is indicated by the widespread, 20° average tilt of the Tertiary rocks toward its axis. This tilt is too widespread to have resulted from faulting, and could only have resulted from downward tilt of the basement surface toward the axis of subsidence. This depression was formed during Tertiary time, either as a gigantic downwarp complementary to adjacent upwarps of the basement surface by great regional compression acting at right angles to the axis of this basin, or by isostasy—that is, by downward sag of this strip of the earth's crust under the increasing weight of material washed onto it. Both these hypotheses imply pliability of the basement complex over large areas.

The east-trending axes of folds formed in the Tertiary formations are somewhat anomalous to the west-northwesterly trend of the axis of the Barstow basin and the northwesterly trends of nearly all the faults within the mapped area. These folds apparently resulted from north-south stress, either regional or local. The anomalous easterly trend of these folds and their stronger compression adjacent to the major northwest-trending fault zones suggest the folds to be subsidiary wrinkles formed in the Tertiary formations where the Barstow basin was transected by the major fault zones. The folds appear to have resulted from right-lateral drag movement, by the opposite blocks, of the underlying more rigid basement complex along these major fault zones. The surface folds formed in the Black Mountain Basalt are generally similar to those of the underlying Tertiary formations and appear likewise to be the result of right-lateral drag movement on these fault zones.

The pattern of steep, northwest-trending faults within the mapped area is well defined. The vertical displacements are small and erratic, with evidence of reversal of displacement along different parts of the same fault zone or even on the same fault. Evidence strongly suggests small right-lateral displacements or components of such displacement on many of the mapped faults. The lateral components of displacement on most, if not all of these faults, may exceed the vertical components, which may be more apparent than real. The three major fault zones are believed to be planes of deep-seated transcurrent shear movement in the basement complex, and the discontinuous faults and associated east-trending folds in the Tertiary and Quaternary formations along these zones to be subsidiary near-surface drag features. These fault zones have many characteristics of the San Andreas fault zone, but on a smaller scale, and are probably local effects of the same regional stress that caused it.

GEOMORPHOLOGY

General Features

The geomorphology of the area within the Fremont Peak and Opal Mountain quadrangles is typical of that of the west central Mojave Desert region. Some of the features within the mapped area were produced by long-continued differential erosion of rocks of varying resistance during late Tertiary and Quaternary time while others are the direct result of tectonic movements in late Quaternary time, and the effects of erosion on them.

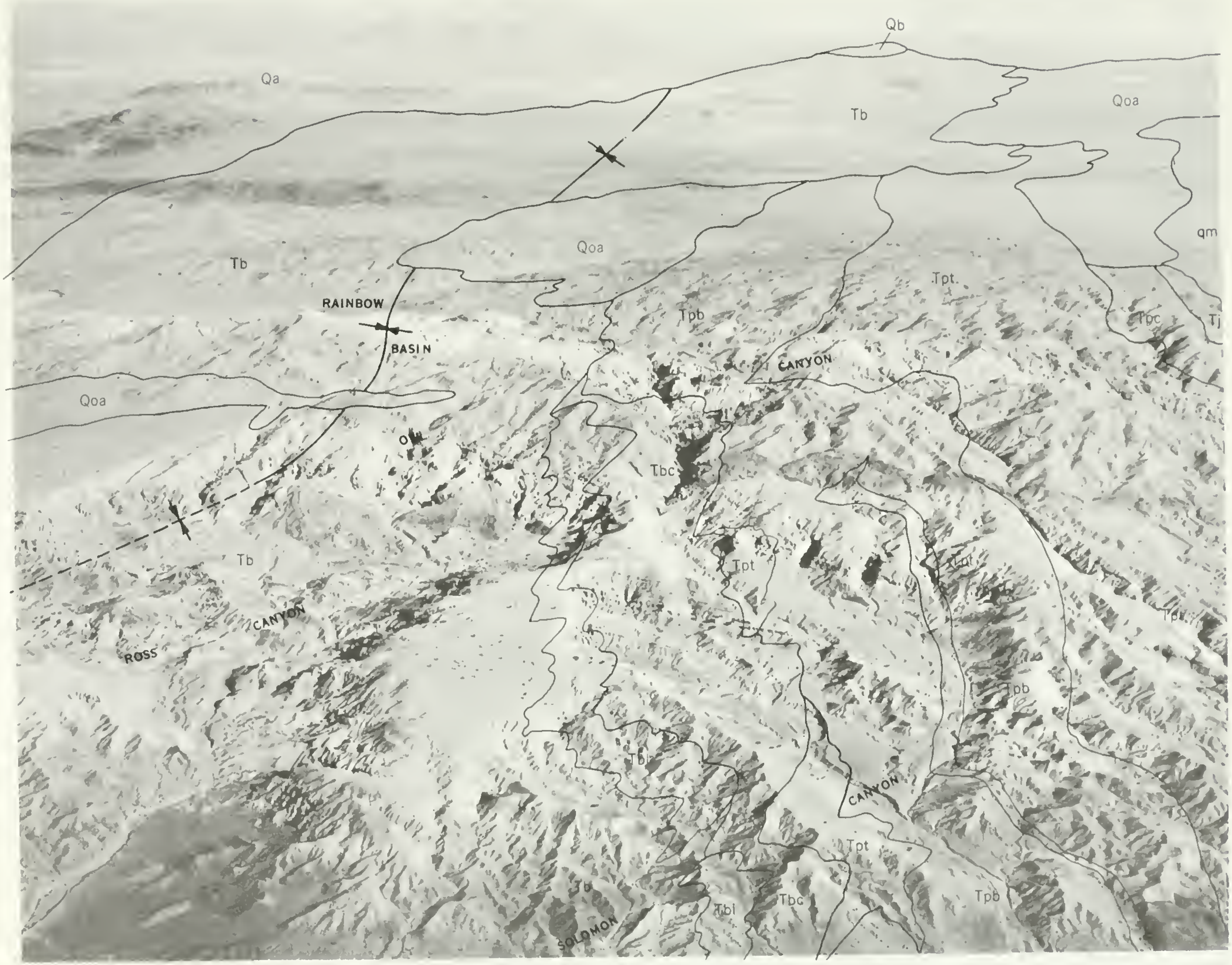

Photo 48. View west over Mud Hills.

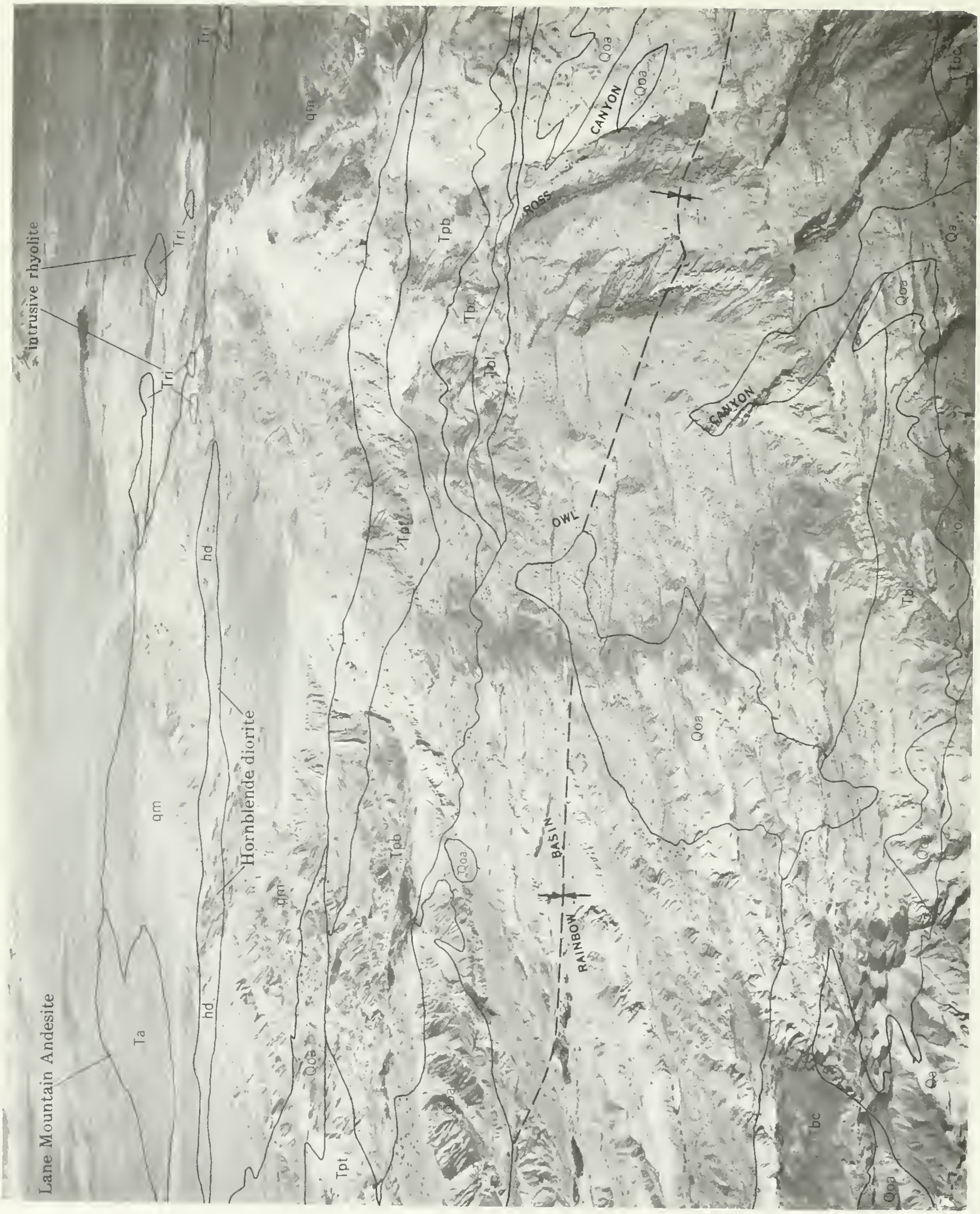

Photo 49. View north across Mud Hills.

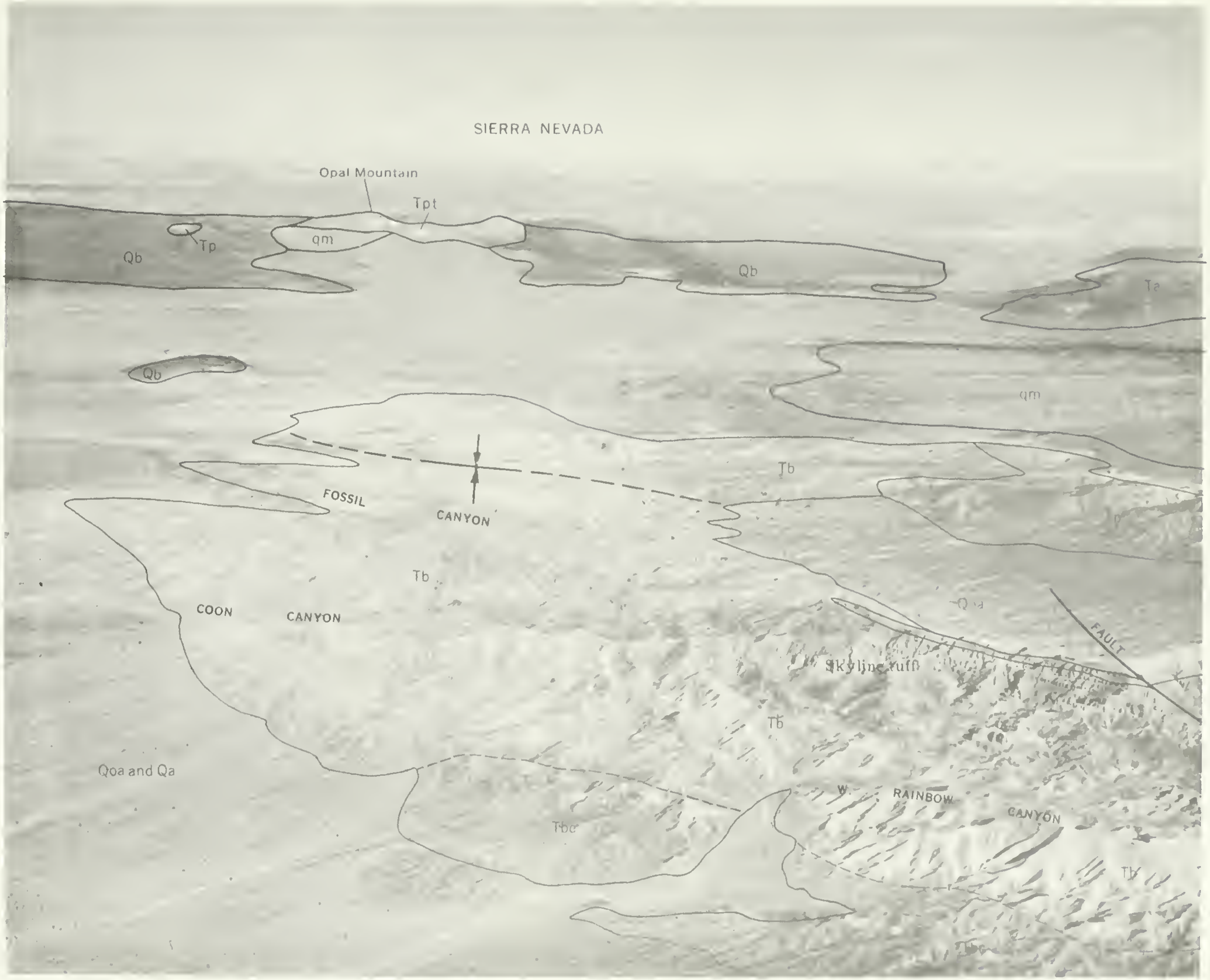

Photo 50. View northwest across western Mud Hills.

Harper Valley

A large part of the southern part of the mapped area is occupied by Harper Valley, a broad undrained basin. The lowest part is a mud flat known as Harper Dry Lake, which covers an area of some 18 square miles at an elevation of 2,020 feet above sea level, the lowest elevation within the mapped area. This is the base level to which the present erosion surface and stream channels are graded, and the mud flat is the sump of the drainage of almost the entire mapped area. This mud flat is generally dry, except briefly after an occasional heavy rain when it may contain a few inches or feet of drainage water.

Northwesterly Harper Valley connects, via a narrow corridor between Fremont Peak and the Gravel Hills, to the valley of Cuddeback Dry Lake (elevation 2,553 feet). This gap contains two small dry mud flats at an elevation of about 2,660 feet. They are the result of the blocking of drainage from this gap by the accumulation of alluvial fan material at its south end, and the formation of a south-facing fault scarp at its north end.

On the west side of Harper Valley the pre-Tertiary crystalline rocks protrude in places a few hundred feet above the flat alluviated surface of the valley to form low isolated hills, their bases buried by alluvium. These hills may be remnants of a once more extensive erosion surface of moderate relief cut in the crystalline rocks.

Harper Valley is an area that has apparently resisted uplift by tectonic forces during late Quaternary time, hence it remains low compared to the surrounding areas, and is being filled with alluvial material from the adjacent highlands.

Area West of Harper Valley

Plain West of Harper Valley. Westerly from Harper Valley the terrain rises gradually to an undulating plain, broken by the Lockhart fault. The terrain south of this fault, somewhat higher than that to the north, is an elevated alluviated surface that is slightly warped and much dissected by washes draining into Harper Valley.

The terrain within four miles north of the Lockhart fault is essentially an elevated pediment surface cut on granitic rocks and is in part covered by a thin veneer of older alluvium. This surface is much dissected, in places by youthful canyons as deep as 200 feet, and the older alluvium is locally eroded away. Northward, this alluvium-covered pediment surface becomes progressively less dissected and rises gradually to the Fremont Peak range.

Fremont Peak Range. Fremont Peak, elevation 4,584 feet, the highest point within the mapped area, is the high point of the Fremont Peak range. From this high point, the range extends some seven miles southeasterly, and nine miles northwesterly of which six miles lies west of the Fremont Peak quadrangle. This range is characterized by a zigzag crestline that generally tapers down from Fremont Peak, and spurs that extend into the adjoining valleys. This range is eroded entirely from the pre-Tertiary crystalline bedrock and its topographic irregularity is the result of long-continued differential erosion of rocks of varying hardness and coherence.

In cross-section profile, the southwestern base of the range is much higher and less well defined than the northeastern base. The alluvium-covered pedimented surface extends up to elevations as high as 3,300 feet on its southwestern flank, which is generally of low relief except at Fremont Peak where it is moderately steep. Viewed from the southwest this range is inconspicuous, with only Fremont Peak looming as a prominent hill. In contrast, the northeastern flank is generally steep and locally precipitous; viewed from the northeast the range appears moderately high and mountainous. The steep rocky slopes of this flank contrast sharply with the alluviated valley surface below, and this flank is characterized by long jutting spurs that separate re-entrants filled with coarse fan alluvium.

The low southeastern part of the Fremont Peak range is eroded mainly from weakly coherent granitic rocks and is reduced to low relief. The northwestern sector of this part of the range is a low pyramidal "dome-shaped" feature eroded from weakly resistant homogeneous quartz diorite, with a smooth surface that slopes at an even gradient of about 3° from its top in all directions. It is similar in shape and size to the "Cima Dome" in the eastern Mojave Desert described in detail by R. P. Sharp (1954, p. 49–52).

The Fremont Peak range is in the maturity stage of the present arid erosion cycle. The higher parts are in the early to middle-maturity stage, but the lower southwestern flank and southeastern parts have reached late maturity. The range appears to be a remnant of mountains once much higher and more extensive, as suggested by its buried northeastern base and by the pediment surface extending outward from its southwestern base. The gentle slope and higher base level of the southwestern flank of the range, as compared to its steep northeast flank, suggest that sometime during Pleistocene time the range was formed, in part by uplift as a southwesterly-tilted block on a possible fault along its now buried northeastern base.

Hills North of Harper Valley

General Features. The wedge-shaped area of hills and low mountains north of Harper Valley stretches from an apex southeast of Cuddeback Dry Lake southeastward some 20 miles to the gap between Harper and Superior Valleys. While this highland is not a continuous range, it is an area of hills and low mountains of which the Gravel Hills, Black Mountain, Opal Mountain, and northeast Black Mountain are parts. Each of these features rises to a high point of over 3,800 feet elevation—more than 1,800 feet higher than Harper Dry Lake. The greatly varied and scenic topography that characterizes these hills is the result of differential erosion of deformed Tertiary volcanic, pyroclastic, and sedimentary formations, and of the overlying Quaternary basalt sheet.

In the section on Structure, part of this highland area was referred to as the Gravel Hills-Black Mountain uplift, elevated in late Quaternary time largely by arching adjacent to the Gravel Hills-Black Mountain fault group of the Harper fault zone. This has produced the moderately steep southwestern front of this highland area which faces Harper Valley along a nearly straight line. The northern and eastern slopes of this highland area are gradual and merge along an irregular base line into the alluviated surfaces of the adjacent valleys that are higher than Harper Valley. This highland area is cut through by the antecedent Black Canyon, which divides the highland into two equal portions: the Gravel Hills on the west and Black Mountain, Opal Mountain, and northeast Black Mountain on the east. Northeast Black Mountain is a local uplift separate from the Gravel Hills-Black Mountain uplift, and was formed by arching in late Quaternary time adjacent to the Blackwater fault zone.

Gravel Hills. The hills that extend from the south end of Cuddeback Dry Lake southeastward to Black Canyon are called the Gravel Hills because they are in large part underlain by gravelly fanglomerate of the Barstow Formation. Exposures of resistant rhyolitic rocks of the Opal Mountain Volcanics form the main east-trending crest of these hills; the north slope is eroded from weakly coherent granitic rocks and the overlying fanglomerate of the Barstow Formation; the south slope from gravels and fanglomerate of the Barstow Formation.

The north slope of these hills is a gently undulating erosion surface that blends into the alluviated surface of Cuddeback Valley to the north. In the northwestern and northeastern parts of the Gravel Hills the surface of deposition of the northward-thinning, undeformed Barstow fanglomerate also blends northward into Cuddeback Valley and into the nearly peneplained surface (now slightly elevated and dissected) cut on the granitic bedrock to the east. This would indicate this erosion surface was formed at the same time the Barstow gravels were deposited, in late Miocene time, and was virtually undisturbed throughout the Quaternary period except for several hundred feet of uplift and local northward tilt during late Pleistocene time. During late Miocene time the erosion surface cut on the granitic bedrock apparently had reached the old age stage of the erosion cycle. As the result of slight uplift in late Pleistocene time, this old erosion surface together with the deposition surface of the Barstow fanglomerate is now being dissected by washes that drain into Cuddeback Valley and upper Black Canyon.

The south slope of the Gravel Hills is steeper than the north slope and is a thoroughly dissected badland surface cut mainly on the weakly resistant, predominantly gravelly sediments of the Barstow Formation. Indeed, numerous washes that drain this slope have cut narrow V-shaped canyons, and the intervening ridges have sharp crests. The large southward-draining wash east of hill 3851 has eroded headward into the north slope of the Gravel Hills into which it is cutting a youthful canyon. Only the largest canyons have deposited small flood plains in their lower courses as they emerge into Harper Valley.

The dissected badland surface cut on the south slope of the Gravel Hills has reached the early maturity stage of the erosion cycle. This surface is for the most part younger than that of the north slope of these hills and was cut during late Pleistocene time after the Gravel Hills were elevated by arching movements.

Opal Mountain and Vicinity. The hills of moderate relief in upper Black Canyon and southeastward to Opal Mountain are differentially eroded from Tertiary volcanic and pyroclastic rocks. The hills eroded from the resistant Opal Mountain Volcanics consequently are rocky, steepsided, and with somewhat rounded summits. The intervening areas, eroded from deformed, less resistant tuff of the Pickhandle Formation, and from gravel of the Barstow Formation, are reduced to lower relief. These formations are in part beveled and covered by a thin capping of resistant, nearly flat-lying Pleistocene Black Mountain Basalt.

The beveled surface beneath this basalt indicates erosion that in places had progressed to the old age stage prior to extrusion of the basalt. After that the area was elevated, along with Black Mountain and the Gravel Hills, several hundred feet above the level of Harper Valley. This uplift is now in the early youthful stage of the erosion cycle.

Black Mountain. Black Mountain, which lies southeast of lower Black Canyon, is a broad basalt-covered mesa that slopes about 2° eastward from a southeast-trending crestal arch 7 miles long. The high point of this arched lava flow at its northwestern end is Black Mountain Peak, elevation 3,941 feet, from which Black Mountain tapers down gradually southeastward into Harper Valley. On the southwest flank of this arch the basalt-covered terrain slopes through a series of undulating benches into Harper Valley. On the steep northwest flank of Black Mountain, facing lower Black Canyon, the Pickhandle and Barstow Formations are exposed below the basaltic lava, which is broken into a series of impressive step-like landslide blocks that slid toward Black Canyon. Associated with these landslides is much loose talus of angular basalt blocks that in most places mask the underlying Tertiary formations.

The Pleistocene basalt that covers Black Mountain is so resistant to erosion that it protects the underlying weakly resistant Pickhandle and Barstow Formations, despite the fact that it is arched and locally deformed. The configuration of Black Mountain, as expressed by the resistant basalt lava sheet that covers it, exactly expresses the geologic structure of this deformed lava sheet. The basalt was poured out over a flat desert floor, and was arched up nearly 2,000 feet above the desert along one or more east-plunging axes adjacent to the Black Mountain fault group, forming Black Mountain. The main axis of the Black Mountain arch is the southeastward extension of the Gravel Hills uplift.

Despite its great amount of uplift by arching movements, the Black Mountain basalt flow is in the early youthful stage of the erosion cycle, and is dissected only in a few places.

Northeast Black Mountain. The basalt-covered mesa east of Opal Mountain is remarkably similar to Black Mountain in almost every aspect and is called northeast Black Mountain. It too slopes about 2° eastward from a 7-mile-long crestal arch that reaches a high point of over 3,800 feet in the northwestern part and tapers down southeastward, and has a steep, abrupt southwestern flank. The lava sheet of this arch and mesa completely conceals the underlying gravel of the Barstow Formation except at its northwestern margin where the Barstow Formation is largely concealed by basalt talus.

The configuration of northeast Black Mountain, as expressed by the basalt lava sheet that covers its surface, is the almost exact expression of its geologic structure after this lava sheet was deformed. As at Black Mountain proper, the basalt lava was poured out onto a flat desert floor and was deformed when the area was elevated several hundred feet as an eastward-tilted block along a southeast-trending arch adjacent to the Blackwater fault zone.

Like Black Mountain proper, the lava sheet that covers northeast Black Mountain has so effectively resisted weathering and erosion that it is practically undissected. Northeast Black Mountain is likewise in the early youthful stage of the present erosion cycle.

Hills East of Harper Valley

Williams Plain. The Williams Plain in the eastern part of the Opal Mountain quadrangle is an undulating surface of low relief cut on granitic rocks. The bedrock surface of Williams Plain gradually rises southward from Superior Valley, at 3,000-foot altitude, to a crest of about 4,000-foot altitude south of Coolgardie Camp. This crest, which reaches a high point of over 4,200 feet within the quadrangle, has a moderately steep, rugged south flank cut on quartz monzonite and is in marked contrast to the nearly peneplained surface of the Williams Plain.

The granitic bedrock of the Williams Plain generally disintegrates readily in the desert climate; much of this old surface is covered by alluvium only a few feet thick. Exposures of more resistant hornblende diorite-gabbro protrude from this surface as low, dark-colored hills. Scattered volcanic necks of resistant rhyolitic rocks also protrude above this surface to form conspicuous isolated knobs with steep sides and rounded summits. Wells Hill, the largest and most prominent of these, rises about 450 feet above the surface of the Plain. The most prominent features of the Williams Plain area are the two flat-topped buttes formed by the resistant lava of the Lane Mountain Andesite. These have precipitous sides; their nearly flat summits are about 700 feet higher than the surface of the Plain.

The Lane Mountain Andesite was extruded onto the old, nearly peneplained, surface eroded in the pre-Tertiary crystalline basement complex of the Williams Plain area, probably in Pliocene time or after deposition of the Miocene Pickhandle and Barstow Formations. The nearly flat summits of the hills of hornblende diorite northeast of the northern butte of Lane Mountain Andesite appear to be remnants of this old erosion surface.

In early(?) Pleistocene time, or after extrusion of the Lane Mountain Andesite, the Williams Plain area was again re-elevated several hundred feet, during which time the old Pliocene(?) erosion surface was largely destroyed, except where it was protected by cappings of the Lane Mountain Andesite. Erosion during Pleistocene time progressed to a surface of very low relief—the old age stage of that erosion cycle. This erosion surface, too, was elevated in late Pleistocene time to its present height, with slight tilt toward Superior and Harper Valleys; it is now being dissected by washes draining westward into Harper Valley.

Southward from the southern rim of the Williams Plain, the eroded surface of the granitic bedrock slopes southward at a steeper gradient. In marked contrast to the Williams Plain, this surface is practically destroyed with V-shaped canyons and sharp divides. This dissection apparently resulted from uplift of the Williams Plain on an axis along or near its southern rim, causing the washes on this steepened southern slope to deepen their channels to the lower base level of the valley to the south, and even to erode headward into the south rim of the Williams Plain.

Mud Hills. The Mud Hills are badlands differentially eroded from tilted strata of the Tertiary formations exposed in the Barstow syncline.

The higher northern part of the Mud Hills is characterized by prominent strike ridges eroded from southward-dipping tuffs and breccias of the Pickhandle Formation. The crests of these strike ridges are accordant, and appear to be remnants of the southward-tilted erosion surface south of the Williams Plain. The gap between these strike ridges and the hills of granitic bedrock to the north is underlain by less resistant strata of the Jackhammer and basal Pickhandle Formations, which have been eroded several hundred feet lower.

The southern and western parts of the Mud Hills are differentially eroded from tilted sedimentary strata of the Barstow Formation to scenically grotesque badlands, in which the clay shales are eroded to light-colored, rounded hills with occasional hard layers cropping out prominently, whereas the sandstones and harder conglomerates are eroded to step-like ledges and fluted bluffs.

The prominent but much dissected mesas of the southern and western parts of the Mud Hills are formed by erosional remnants of Pleistocene alluvium that caps the beveled surface of the synclinally folded Barstow Formation. This older alluvium surface which is roughly 200 feet higher than the adjacent valley area to the south and west, thins out and laps northward against exposures of the Pickhandle Formation in the higher northern portion of the Mud Hills. The older alluvium extends around the west end of these hills, eastward into the gap to the north, and also into canyons eroded into the granitic bedrock north of this gap. The eroded surface upon which the older alluvium was deposited is in part lower, hence younger, than the old southward-sloping erosion surface south of the Williams Plain. Deposition of the older alluvium upon the eroded surface of the Mud Hills was followed by about 200 feet of recurrent uplift of the

Mud Hills area in late Pleistocene time, during and after which the older alluvium was dissected. The washes then deepened their channels to the present base level of the valley to the south, cutting narrow canyons in the underlying Tertiary formations. Erosion in late Pleistocene and Recent time has now progressed to the late youth or early maturity stage.

Correlation of Erosion Surfaces

In the Mojave Desert, erosion of highland areas and deposition of the eroded detritus in the intervening basins was a continuous process during the Cenozoic era so that definite correlations of erosion surfaces are not possible. However, within the mapped area general correlations can be determined from the formations that cover each erosion surface, or from the surfaces of deposition of the formations cut by each erosion surface.

The late Miocene erosion surface of low relief cut after deposition of the Pickhandle Formation and during or after deposition of the Barstow Formation is largely destroyed, except at the extreme northern part of the mapped area north of the Gravel Hills, where it is preserved as an undulating surface of low relief cut on the crystalline basement rocks. It is in part covered by a thin deposit of the northernmost extent of the fanglomerate facies of the Barstow Formation and in part blends into its surface of deposition.

The Pliocene(?) erosion surface of low relief cut prior to eruption of the Lane Mountain Andesite is largely destroyed, except for remnants on the Williams Plain. There it is preserved only where it is protected by the two cappings of the Lane Mountain Andesite that rest on it. The nearly flat summits of the hills formed by resistant hornblende diorite just northeast of the northern butte of the Lane Mountain Andesite may be other remnants of this Pliocene(?) erosion surface.

Pleistocene erosion surfaces of low relief cut on the crystalline basement complex are still preserved on the low hills north of the Lockhart fault and west of Harper Valley and on the southwestern flank of the Fremont Peak range and its pediments to the southwest. All these surfaces are partly covered by a thin veneer of Pleistocene older alluvium or blend into its surface of deposition.

Other Pleistocene erosion surfaces of low relief were no doubt cut on the deformed Tertiary formations of the highland areas north of Harper Valley prior to extrusion of the Black Mountain Basalt. On the Gravel Hills this old erosion surface is largely destroyed, especially where cut on the soft fanglomerate facies of the Barstow Formation. In the vicinity of Opal Mountain it is partly preserved where it blends into the surface covered by the Black Mountain Basalt. On Black Mountain and northeast Black Mountain this old erosion surface, which is covered by the Black Mountain Basalt, is deformed by tectonic movements but is preserved from erosion by the protective capping of the Black Mountain Basalt.

East of Harper Valley the Pleistocene erosion surface of low relief is still preserved on the Williams Plain where it is cut on the crystalline basement complex; westward where it slopes under Harper Valley it is covered by the Pleistocene older alluvium. On the steep south flank of the ridge at the south rim of Williams Plain, the Pleistocene erosion surface is largely destroyed, but is partly preserved in the Mud Hills to the south where it is cut on the deformed Tertiary rocks of the Barstow syncline, and is in part covered by Pleistocene older alluvium.

All the areas adjacent to Harper Valley that were elevated above its present base level in late Pleistocene time are now being dissected by washes that are deepening their channels to this level.

Quaternary Physiographic Evolution and Drainage History

It may be concluded that in early Pleistocene time diastrophism resulted in uplifts of moderate relief within the Fremont Peak and Opal Mountain quadrangles. The Fremont Peak range was probably mountainous, and the area to the south moderately hilly. The Gravel Hills-Opal Mountain area and the area to the north probably had moderate relief as did the Williams Plain-Mud Hills area. These highland areas were pedimented and eroded down to subdued relief later in Pleistocene time. The detritus eroded from these areas was deposited as alluvial material on the pedimented and peneplained surfaces of the southern, central, and northeastern parts of the map area to form what are now Harper and Superior Valleys. These two valleys were then joined across the sites later occupied by Black Mountain and northeast Black Mountain. Harper Valley may also have merged with Cuddeback Valley to the northwest.

The drainage system formed since the early Pleistocene diastrophism is largely conjectural, but it appears that Cuddeback Valley drained southeastward, and Superior Valley southwestward, into Harper Valley, and that Harper Valley drained southeastward via Hinkley Valley into the Mojave River, which may have come into existence in early or middle Pleistocene time.

Sometime in the middle(?) or late Pleistocene time the Black Mountain Basalt was erupted from at least two major vents, one on the Harper fault zone and the other from the Blackwater fault zone. It poured out as an extensive lava sheet and covered a large part of Harper Valley, the pedimented surface of the Opal Mountain area, and the southwestern part of Superior Valley.

The late Pleistocene diastrophism consisted largely of uplift on the Harper and Blackwater-Mud Hills fault zones, to form the present topography. Arching of the block northeast of the Gravel Hills-Black Mountain fault zones caused renewed uplift of the Gravel Hills, and arching of part of the basalt-covered area of Harper Valley to form Black Mountain. At the same time, arching movements on the block northeast of the Blackwater fault caused uplift of the basalt-covered southwestern part of Superior Valley to create northeast Black Mountain. Harper and Superior Valleys were then separated by these new basalt-covered arches. Williams Plain and the Mud Hills became re-elevated several hundred feet, in part by uplift on the Mud Hills faults and probably in part by arching along the ridge north of the Mud Hills.

The area west of Harper Valley was practically unaffected by the late Pleistocene orogeny except for several hundred feet of renewed uplift of the Fremont Peak range and the area to the south.

These uplifts disrupted the established drainage system. The probable southeastward drainage from Cuddeback Valley into Harper Valley was blocked by the uplift of the Gravel Hills on the Cuddeback and Gravel Hills faults. Alluvial fans from erosion of these hills and the Fremont Peak range to the southwest merged in the narrow corridor between them, not only to block southward drainage from Cuddeback Valley, but to cause a partial reversal of drainage into that valley. The southward-facing scarp of a fault that cuts the Recent alluvium 2 miles north of Fremont Peak blocked the reverse northward drainage into Cuddeback Valley, to form a small dry lake in this gap. With its outward drainage blocked, Cuddeback Valley became an undrained basin, containing Cuddeback Dry Lake at an altitude of 2,560 feet above sea level.

Uplift of the Gravel Hills and Black Mountain caused washes previously established in the Gravel Hills to deepen their channels, and new washes to form on the Black Mountain arch. Black Canyon, which drained the highland area including Slocum Mountain to the north, apparently maintained its course through this uplift, thereby cutting a deep canyon across it. The uplift of northeast Black Mountain diverted the southwestward drainage from Superior Valley, so that this valley in part drained around the east side of this uplift, and in part around the north side through Slocum Wash into Black Canyon. The eastern drainage eventually became blocked, probably by continued uplift of this arch and the Williams Plain area to the east, so that all the drainage from this valley had to go into Black Canyon. This, too, is now becoming blocked with the continued uplift of Gravel Hills-Black Mountain-Opal Mountain area, which seems to exceed the rate of erosion through Slocum Wash. Superior Valley is now becoming an enclosed basin with three dry lakes in it, and several mud flats in Slocum Wash, all at altitudes of about 3,000 feet.

In late Pleistocene time drainage from Harper Valley was blocked, so this valley, too, became an undrained basin with the formation of Harper Lake at an elevation of 2,020 feet. This resulted either from slight uplift of the area south of Harper Valley, or from the build-up of a broad alluvial fan by the Mojave River over the triangular area between Hinkley, Hodge, and west Barstow.

Evidence suggests that either in very late Pleistocene or possibly in early Recent time, the lower part of Harper Valley was flooded by waters of a large shallow lake, Lake Harper, of which the mud flat of Harper Dry Lake is a remnant. The evidence of this large ancient lake is several old shore lines barely visible on aerial photographs, but not on the ground; they are shown on the geologic map. The highest shore line is at about the 2,160-foot contour line, from 1 to more than 2 miles from the margin of the present Harper Dry Lake. As the altitude of the present mud flat is 2,020 feet above sea level, Lake Harper may once have been as deep as 140 feet. Several other shore lines appear at lower levels, of which the most prominent is at about the 2,080-foot contour on the east side of the present playa.

The most prominent shore lines are at least four parallel ones in Sec. 35, T. 11 N., R. 3 W., southeast of Harper Dry Lake, at the southeastern border of the map area. They are between the approximate 2,120 and 2,160-foot contours, and are traceable for about two miles. North, west, and south of Harper Dry Lake no shore lines are clearly visible, although one is suggested near the 2,160-foot contour line, below which the alluvium is predominantly fine silt, while above it is sand and gravelly sand.

The shore line of Lake Harper in which fine sand, silt, and clay was deposited, extends 5 or 6 miles south of the Opal Mountain quadrangle. Apparently it flooded the flat portion of Harper Valley between Hinkley and the hills to the east. Some water from the Mojave River may have flowed into this ancient lake, as suggested by Thompson (1929, p. 270), before the river deepened its channel some 50 feet below the valley surface between Hodge and Barstow. This is suggested by the very gradual northward slope of the valley surface between Hodge and Harper Dry Lake.

In Superior Valley no evidence of a large lake is seen, and no shore lines are visible on aerial photographs. This is to be expected, because until early Recent time Superior Valley apparently drained through Slocum Wash and Black Canyon into Harper Valley, 1,000 feet lower.

OUTLINE OF GEOLOGIC HISTORY *

Precambrian(?) Deposition.

1. Deposition of ancient rocks now represented by Waterman Gneissic Complex and intercalated marble, probably as argillaceous and arkosic sandy sediments and limestone; accumulation to great thickness under a probable widespread sea.

Precambrian(?) Diastrophism.

2. Emergence of area from sea.

3. Strong deformation of ancient sediments now represented by Waterman Gneissic Complex, accompanied by uplift and erosion.

4. Severe regional thermodynamic metamorphism of sediments represented by Waterman Gneissic Complex, causing crystallization of shale and arkosic sandstone to schist and gneiss and carbonate rocks to white marble.

5. Probable severe erosion of area to low relief.

Late Paleozoic Deposition(?).

6. Probable submergence of area under widespread shallow sea.

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* Numbers indicate events in chronologic order: letters indicate local events that are synchronous.

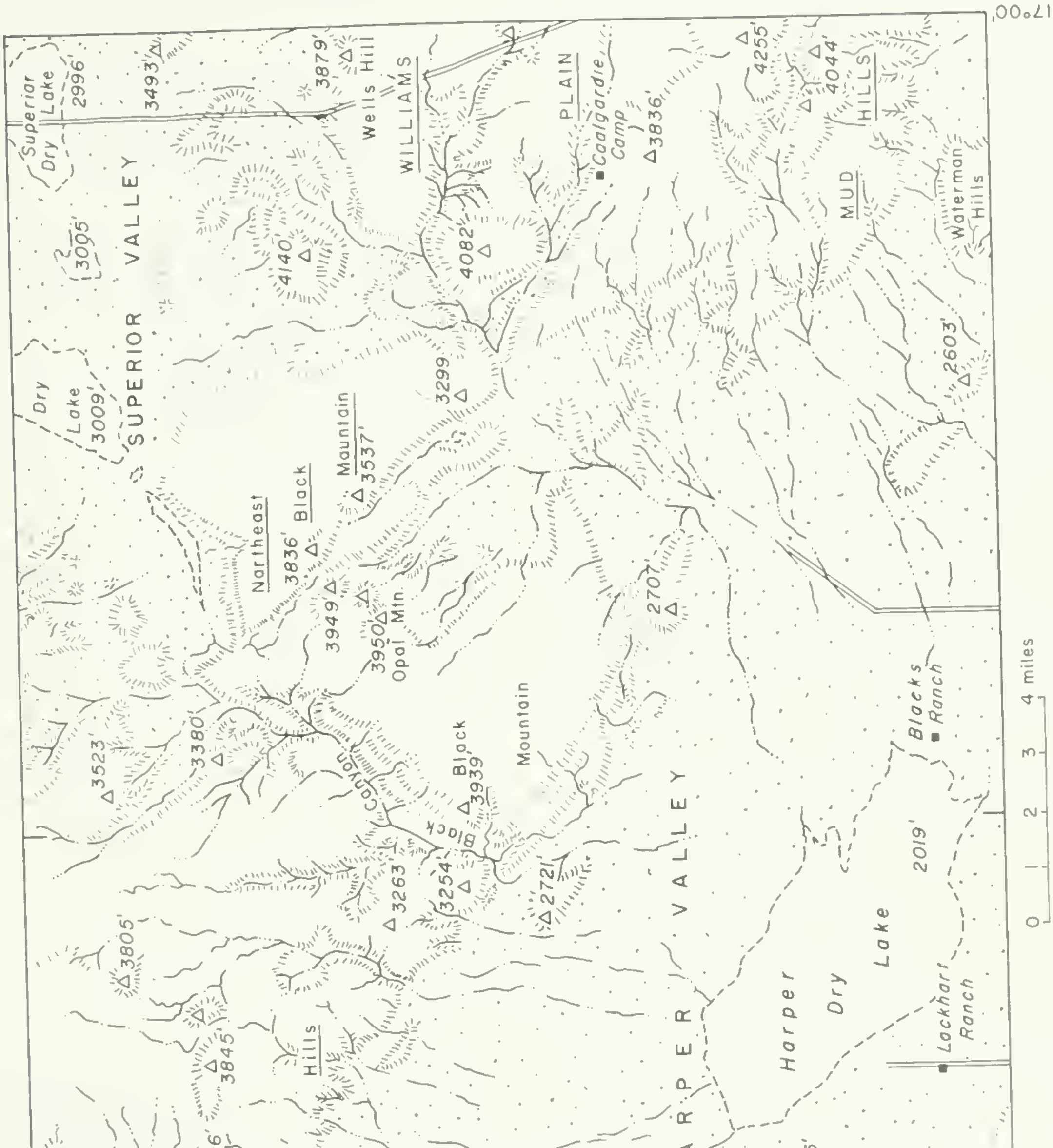

Figure 4. Physiographic map of the Fremont Peak and Opal Mountain quadrangles.

7. Probable deposition of clay, siltstone, sandstone, and carbonate on sea floor and accumulation to great thickness, as indicated by presence of thick formations of late Paleozoic age in Calico Mountains, Quartzite Mountain, and Shadow Mountains, near mapped area.

Jura-Cretaceous(?) Diastrophism (Nevadan Orogeny).

8. Emergence of area from sea.

9. Severe deformation of Precambrian(?) and Paleozoic formations, accompanied by uplift and erosion.

10. Moderate regional thermodynamic metamorphism of Precambrian(?) and Paleozoic formations, with further recrystallization of the Waterman Gneissic Complex, in places to gneissoid quartz diorite; and crystallization of Paleozoic strata to slates, hornfels, quartzite, and carbonate rocks.

11. Widespread batholithic invasion of siliceous magma into the Waterman Gneissic Complex and Paleozoic formations, in most places completely digesting them during climax of Nevadan orogeny; hornblende diorite formed locally, probably by segregation of ferromagnesian material from pre-existing rocks during upward advance of siliceous magma which eventually crystallized mainly to quartz monzonite; region probably elevated to mountainous highland during Nevadan orogeny.

Injection of siliceous magma into fractures of crystallized quartz monzonite and associated rocks, and crystallization of pegmatite and aplite during final stage of Nevadan orogeny.

Cretaceous-Eocene Erosion.

12. Long-continued erosion during late Cretaceous time of mountainous highland built up during Nevadan orogeny; removal of Paleozoic formations from mapped area; region remained high possibly by recurrent uplifts; eroded material carried outward.

13. Minor igneous activity in late Cretaceous(?) or early Tertiary(?) time with injections of siliceous magma into parallel fractures of country rock in Fremont Peak area, and crystallization to quartz latite.

14. Continued erosion of highland during Eocene time to surface of low relief.

Oligocene(?)—Early(?) Miocene Diastrophism.

15. Uplift of southwestern area, including sites of later-formed Fremont Peak range and southwestern Harper Valley, to a probable mountainous highland; probable early downwarping of adjacent area to northeast (including sites of northeastern Harper Valley, Gravel Hills, Black Mountain, Opal Mountain, and Mud Hills) to form the Barstow basin.

16. Erosion of highland area and deposition of terrestrial sediments of Jackhammer Formation at site of Mud Hills in Barstow basin; minor eruption of basalt and ash.

Middle(?) Miocene Volcanism and Deposition.

17. Explosive volcanic activity with eruptions of rhyolitic ash, pumice, and volcanic rock fragments from vents at sites of northern Gravel Hills and Opal Mountain areas; erupted pyroclastic material spewed over valley of Barstow basin and probably over area of low relief to the north to accumulate as the Pickhandle Formation. During deposition of this formation the following local events occurred, in part contemporaneously:

A. Eruptions of rhyolitic flow-breccias from some vents and accumulation as small volcanic piles.

B. Eventual filling of all vents with rhyolitic plugs of Opal Mountain Volcanics.

C. Local eruption of a basalt flow in Opal Mountain area.

D. Local deposition of granitic landslide breccias into valley of Barstow basin at sites of the Mud Hills and Gravel Hills; breccias probably derived from rugged mountains uplifted nearby.

Middle Miocene Diastrophism.

18. Intensified downwarping of Barstow basin, and uplift of areas to southwest and northeast, as follows:

A. Possible recurrent uplift of area southwest of valley of Barstow basin.

B. Upwarp of area north of Barstow basin, that is the entire area north of sites of Gravel Hills, Black Mountain, and Mud Hills, causing southward tilt of Jackhammer and Pickhandle Formations toward axis of Barstow basin; erosion of these formations, of Opal Mountain Volcanics, and of granitic bedrock.

C. Continued subsidence of Barstow basin as a narrow trough-like downwarp along a northwest-trending axis, with contemporaneous deposition of following facies of basal part of Barstow Formation:

  a. Owl Canyon Conglomerate as a fan deposit at site of Mud Hills;

  b. Fine clays in a shallow lake at site of lower Black Canyon;

  c. Stream-laid tuffaceous sands at site of eastern Gravel Hills;

  d. Coarse fanglomerate at site of western Gravel Hills.

Late Miocene Diastrophism and Deposition.

19. Continued and intensified downwarp of Barstow basin, and uplift and erosion of areas to southwest and northeast, as follows:

A. Continued and intensified uplift of area southwest of Barstow basin to a probable mountainous highland of granitic rocks; highland severely eroded by torrential downpours that washed much granitic detritus into Barstow basin.

B. Continued and intensified uplift of area north of Barstow basin (including sites of Williams Plain, Superior Valley, Slocum Mountain, and areas north of Opal Mountain and Gravel Hills) to a probable semimountainous highland. Removal by erosion of Jackhammer and Pickhandle Formations (if ever deposited there) and the exposing of granitic rocks and Tertiary rhyolitic intrusive rocks; highland severely eroded by torrential downpours that washed granitic and volcanic detritus into Barstow basin; highland probably eventually eroded to low relief.

C. Continued and accelerated subsidence of Barstow basin and rapid accumulation of alluvial sediments of the Barstow Formation of which the following local facies were deposited:

a. Coarse granitic detritus derived from highland to southwest deposited as coarse alluvial fans along southwestern margin of Barstow basin, with maximum thickness of some 4,500 feet deposited at site of the Gravel Hills and at least 2,500 feet at site of southwestern Mud Hills;

b. Volcanic and minor granitic detritus derived from highlands to northeast, deposited as alluvial fans along northern margin of Barstow basin, with maximum thickness of some 2,500 feet accumulated at site of eastern Gravel Hills;

c. Terrestrial gravels, sands, and silts deposited as outwash material from coarse alluvial fans in lower flood-plain areas of valley at sites of Black Mountain and parts of Mud Hills;

d. Fine-grained silts, clays, and thin calcareous layers, also some thin layers of rhyolitic ash, deposited in a shallow lake or lakes at site of eastern Mud Hills, in lowest part of Barstow basin, the shore line of which shifted as it received drainage water or lost it through evaporation, or as delta deposits of sand and gravel were locally built up.

Pliocene Diastrophism.

20. Widespread diastrophism, uplift, and erosion, but eroded material apparently not deposited within area; possibly entire area affected as follows:

A. Recurrent uplift of area southwest of Barstow basin; possible uplift of Fremont Peak range as a southwest-tilted block on a possible fault along its northeastern base.

B. Recurrent uplift of area northeast of Barstow basin.

C. Uplift of portions of Barstow basin, probably by initial movements on Blackwater and Harper fault zones; formation of Barstow syncline and initial uplift of Mud Hills; also formation of Gravel Hills syncline and Black Canyon anticline, and initial uplift of Gravel Hills to form badland areas.

D. Erosion of all elevated areas to low relief during final stages of diastrophism, with probable development of old age stage of erosion cycle in most areas.

Late(?) Pliocene Volcanism.

21. Local eruptions of Lane Mountain Andesite on the nearly peneplained granitic surface now known as the Williams Plain.

Early and Middle(?) Pleistocene Diastrophism, Volcanism and Deposition.

22. Continued or locally recurrent uplift of areas uplifted during Pliocene orogeny, as follows:

A. Continued or renewed uplift of Fremont Peak range, possibly to rugged mountains, on possible fault along its northeastern base; probable slight uplift of area west of Harper Valley.

B. Continued or recurrent uplift of area northeast of site of Gravel Hills; also the Slocum Mountain area.

C. Slight recurrent uplift of Williams Plain area.

D. Probable uplift of granitic hills south of site of Mud Hills.

E. Possible recurrent movement on Blackwater and Harper fault zones and recurrent compression of Barstow syncline, Gravel Hills syncline and Black Canyon anticline.

F. Stabilization of intervening areas to form Harper-Superior Valley lowlands.

23. Erosion of uplifted areas to moderate to low relief, margins reduced to broad pediments; deposition of eroded detritus on lowlands of Superior Valley area and on adjacent pediments.

24. Eruption of Black Mountain Basalt from fissure vents on or near Blackwater and Harper fault zones; basalt spread as thin lava flow over lowland area.

25. Eventual erosion of all uplifted areas to low relief; deposition of eroded material as older alluvium in Harper and Superior Valleys and on most pediments.

Late Pleistocene Diastrophism and Deposition.

26. Strong recurrent movements on major fault zones and uplift of adjacent areas, as follows:

A. Recurrent movements on Blackwater-Mud Hills fault zone, with uplift of area to northeast to form northeast Black Mountain, Williams Plain and Mud Hills.

B. Recurrent movements on Harper fault zone, with uplift of area to northeast to form Gravel Hills and Black Mountain.

C. Recurrent uplift of Fremont Peak range probably on a fault(?) bordering its northeastern base, range tilted gently southwest as a block.

D. Movement on Lockhart faults, with slight uplift of area southwest of main fault.

E. Continued deposition of older alluvium in Superior and Harper Valleys.

Recent Movements and Deposition.

27. Continuation of previous event, with drainage as outlined under "Quaternary physiographic evolution and drainage history."

MINERAL RESOURCES

Gold

Coolgardie District. Coolgardie Camp, probably named after the Coolgardie gold district of Australia, is the center of numerous shallow placer gold diggings which have been worked sporadically by prospectors for many years. Due to the scarcity of water, the placers have to be worked by "dry washing" in which machines called "dry washers" use bellows to blow away the lighter materials. The heavier residue is sometimes "panned" without water, except in the final stage, when a very little water is used. The area is literally honeycombed with diggings, but production of gold apparently has been small, and there are no mills.

Nearly all the diggings are only a few feet deep and are sunk in the thin layer of Quaternary alluvial gravels that lie on granitic rocks. The gravels are composed of semirounded cobbles of dioritic and granitic rocks in a matrix of ill-sorted arkosic sand. The gravel commonly contains float of heavy nonmagnetic black iron oxide weathered out of the hornblende diorite outcrops south of Coolgardie Camp. Gold in small amounts has been found at or near the base of the gravel, and in fractures of the weathered surface of the underlying plutonic rocks. The source of the gold is probably quartz veinlets in the large exposure of hornblende diorite upslope to the south. The hornblende diorite itself may also contain traces of disseminated gold that could be concentrated at the base of the gravels as the plutonic rocks of the area were being weathered and eroded to a surface of low relief throughout middle and late Pleistocene time.

In the Coolgardie district several prospect shafts were sunk into the plutonic rocks, especially in fracture zones in the dioritic rocks. The northwest-trending fault zone a mile and a half east of Coolgardie Camp has been much prospected. However, it is unlikely that any of these fracture-zone prospects yielded gold in paying quantities. All are now abandoned.

Fremont Peak District. There are one gold mine and several prospects in the Fremont Peak range. The Fremont Peak (Gateway) mine, owned by Mrs. W. O. Walker, is located half a mile west of Fremont Peak. The workings are developed along a series of parallel quartz veins, 1 to 4 feet wide, which strike generally northeast and dip steeply northwest. Wall rock is quartz monzonite. Gold, pyrite, and arsenopyrite occur in veins and also along the contact between quartz monzonite and rhyolitic dikes. Workings consist of a 185-foot shaft inclined 20° N. from vertical, sunk on an iron-stained quartz vein in quartz monzonite, with three levels and about 3,250 feet of drifts and cross cuts. There are also three adits 60 to 200 feet long on the property. Milling equipment consists of an amalgamation mill. The mine is now idle. (Wright et al., 1953, tab. list 35).

A prospect at the west end of the north slope of Fremont Peak range, on the G. S. Jones group of six lode claims, is located 2 miles northwest of Fremont Peak. Workings consist of three closely spaced adits driven southeastward along the strike of fractured, iron-stained rhyolitic dikes which cut quartz monzonite and which contain some quartz stringers. The longest adit is about 100 feet long. At the end of it is a raise to the surface. Gold probably was found at the contact of the quartz monzonite and the rhyolite dike but apparently not in paying quantities.

Several other gold prospects, which apparently did not pay out, are located on various claims in the Fremont Peak range and are indicated by prospect symbols on the map (plate 1). Nearly all are located in fracture zones in quartz diorite gneiss or in quartz monzonite. One of these is a 60-foot vertical shaft a mile northeast of Fremont Peak. Another, located 2 miles southeast of this peak, is a deeper shaft inclined westward along a fracture zone in quartz diorite gneiss. One mile southeast of the latter shaft are several shallow shafts. In the foothills 2 miles east of Fremont Peak there are shallow diggings that never progressed beyond assessment work.

Two miles northeast of Fremont Peak there is an adit driven about 90 feet northeastward into moderately indurated fanglomerate of the Barstow Formation. On the adjacent flat are concrete foundations of a mill labeled "Hamburger Mill (Site)" on map, in sec. 30, T. 31 S., R. 43 E. This enterprise apparently never went beyond the prospect stage.

Strontianite

Two deposits of strontianite (strontium carbonate) occur in the Barstow Formation in the eastern Mud Hills. These deposits were described in an early paper by Knopf (1918, p. 257–270) and were described and mapped in detail by Durrell (1953, p. 23–32). They are known as the Solomon deposit and the Ross deposit.

Solomon Strontianite Deposit. The Solomon strontianite deposit, owned by C. Solomon of San Francisco, is in sec. 20, T. 11 N., R 1 W., 2 miles north of the southeast corner of Opal Mountain quadrangle. This deposit was discovered in 1915, and the only known production was "several tons" of strontianite rock shipped in 1917.

The strontianite nodules occur in tuffaceous clays of the lower part of the Barstow Formation. The strontianite is confined to two beds that lie within a 60-foot bed of clay shale.

The strontianite nodules occur in tuffaceous clays whose bedding planes cut the strontianite nodules. On the basis of these relationships Durrell (1953, p. 32) believed that the strontianite nodules were formed by replacement of tuffaceous clays, and not by replacement of limestones as believed by Knopf (1918, p. 264). Durrell (1953, p. 32–33) suggests that the strontium carbonate was either an original constituent of the sediments, or was introduced in hydrothermal solutions; he favors the latter.

The areal distribution of the strontianite-bearing clays of the Solomon deposit is irregular, because the clays crop out within strata that dip at low angles (generally less than 20°), are compressed into minor folds, and are locally faulted. They crop out in a badland area having about 200 feet of relief. The strontianite-bearing beds dip generally southward and are traceable along strike for about 3,000 feet. To the west, they thin out under a cover of Quaternary gravel, and they are concealed by alluvium to the east. The Solomon deposits are cut by many faults of small displacement, most of which are steep normal faults with northwesterly trends, as mapped by Durrell (1953, pl. 5).

Although most of the bodies of strontianite rock of the Solomon deposit are small, there are many of them, so that the total tonnage is fairly large. A few masses were as much as 2 feet thick and 40 feet long at the surface. The largest number of strontianite bodies probably is in the lower beds exposed in the central portion of the deposit. These bodies were mined in the early days.

Reserves of the Solomon deposit were estimated by Durrell (1953, p. 33) to be at least 40,000 tons of strontianite rock in bodies averaging 5 percent or more of strontianite. This would be equivalent to 290,000 tons of strontium carbonate. This estimate is conservative, for in much of the lower beds and in parts of the upper beds, the strontianite rock far exceeds 5 percent by volume.

Ross Strontianite Deposit. The Ross strontianite deposit, owned by F. T. Ross of Los Angeles, is in the NE¼ sec. 30, T. 11 N., R. 1 W., three-quarters of a mile southwest of the Solomon deposit, and just east of the lower part of Owl Canyon. No strontianite has been mined from it.

Strontianite occurs in the interval of greenish clay within the Barstow Formation. The strata dip from 20° to 50° north. The strontianite-bearing clay interval is 311 feet thick, according to Durrell (1953, p. 34). The top is stratigraphically about 600 feet below the lower marker tuff horizon (see description of the type section of the Barstow Formation), and the base is about 880 feet above the top of the Owl Conglomerate Member that crops out along the southern margin of the Mud Hills.

Durrell describes the amount of ore as follows (1953, p. 34):

> The exposed area containing the strontianite rock is 294,000 square feet. Using the value of 4.4 percent as the fraction of the strontianite rock, and 200 pounds per cubic foot for the weight of the strontianite rock, about 13,000 tons of strontianite rock is present for each 10 feet of depth. A possible additional 1,000 to 1,500 tons per 10 feet of depth is concealed beneath the terrace near the east end of the deposit. Should the deposit continue down dip for 100 feet, the reserves would amount to around 140,000 tons of strontianite rock.

Radioactive Minerals

Traces of unidentified radioactive material have been found in the Barstow Formation of the Mud Hills. Also minute amounts of a light-yellow radioactive mineral, probably autunite, were found in fracture surfaces of clay shale below the basalt flow in the Barstow Formation in the Black Canyon anticline.

In the southwestern part of the Mud Hills anomalous radioactivity was detected by J. G. Coon in the Coon claims in sec. 23(?) T. 11 N., R. 2 W. The radioactivity amounts to a maximum of 0.5 MR/hr., according to Walker, Lovering, and Stephens (1956, p. 20) and occurs in fossil bone fragments and in calcareous sandstone and clay beds that contain the bone fragments. The beds dip steeply northeast and occur 500 to 600 feet stratigraphically below the lower marker tuff (see measured section of Barstow Formation). The radioactive bone fragments and beds that contain them are strongly reactive to phosphate tests but no uranium minerals were definitely identified. Walker, Lovering, and Stephens (1956, p. 20) expressed the opinion that uranium occurs as traces in the phosphate mineral present in the bone material and possibly in a phosphate cement in the sandstone.

Limestone

In the low hills west of Harper Valley are small deposits of limestone within the Waterman Gneissic Complex. It is doubtful if these are suitable for use in cement manufacture as they occur as beds not over 15 feet thick, and they may have too high a magnesium content.

Feldspar

The largest deposit of feldspar in the area is the White Butte deposit, well exposed on a low white hill 9 miles east northeast of Fremont Peak. This deposit is owned by Interpace (formerly Gladding, McBean and Company) of Los Angeles. It is a pod-shaped pegmatite body about 300 feet long and nearly 200 feet in maximum width, of feldspar and quartz cutting quartz monzonite. The mass is composed mostly of pinkish-white perthitic microcline, but contains lenticular pods of white quartz as much as 60 feet long and 10 feet wide oriented parallel to the length of the body. Minor constituents include biotite, sericite, and white albite feldspar. More than two-thirds of the body appears to be feldspar. Both the feldspar and quartz are extremely brittle and have closely spaced fractures, which facilitates quarrying operations.

The quarry is roughly 200 feet long by 121 feet wide by 30 feet deep. Remnants of the larger quartz bodies remain in the cut. About 17,000 tons of ceramic-grade feldspar has been quarried from this deposit since it was opened in 1940 (Wright et al., 1953, p. 165).

Besides the White Butte deposit, there are numerous low-grade deposits of feldspar in the form of pegmatite dikes in the vicinity of hill 3805 to the southeast of the White Butte deposit. However, exploitation of these would require extensive sampling to determine the percentage of commercial potassium feldspar, and would require hand sorting to separate it from the plagioclase and quartz. The pegmatite dikes are described under Pegmatite and Aplite.

Quartz

Lenticular veins of milky quartz are found at several localities in granitic rocks. The largest mass occurs with feldspar in the White Butte deposit, described under feldspar. Half a mile south of Opal Mountain is a mass of quartz about 20 feet wide associated with about 25 percent feldspar and enclosed in quartz monzonite. Other small pods of quartz occur in a similar environment west of Wells Hill, in sec. 11, T. 32 S., R. 46 E. Two miles southeast of Coolgardie Camp, in sec. 5, T. 12 N., R. 1 W., is a quartz vein which reaches a thickness of 15 feet. It trends northeast and dips 70° W. for a strike distance of nearly ⅓ of a mile. This vein has been prospected by a deep inclined shaft sunk on the hanging wall side of the vein in search of gold.

Perlite

Perlite, the hydrous, minutely fractured form of obsidian, has the property of expanding during calcination. Under properly controlled heat conditions some perlites expand to as much as 20 times their original volume. Expanded perlite is widely used as an insulating material.

Black Canyon-Opal Mountain Area

The Black Canyon-Opal Mountain volcanic field includes many deposits of perlite. The largest and most accessible of these are just west of the main fork of upper Black Canyon. The Hicks deposit, operated intermittently by R. E. Hicks of Huntington Park, is located in the SE ¼ sec. 35, T. 31 S., R. 44 E., M.D. B. and M., 1 mile west of Opal Camp. The perlite is exposed on a low isolated hill in a 60-foot-wide zone in rhyolite or dacite. Some objectionable rhyolitic nodules are found in it. The perlite zone probably continues a short distance both northeast and northwest of the Hicks quarry. It dips steeply and is found closely adjoining, on the north, a rhyolitic breccia.

Several small masses of perlite lie in the S ½ sec. 26, T. 31 S., R. 44 E., about a mile north of the Hicks deposit. These occur as lenticular zones, as much as 40 feet wide, adjacent to several small plugs of rhyolitic rock. Most of the rock contains nonexpansible nodules. Small tonnages were quarried from two large pits, and additional prospecting has been done by scraping off the overburden.

A number of perlite deposits crop out in the vicinity of Opal Camp (also called Scouts Cove), and several large, irregular masses up to 500 feet wide lie in a small canyon 1 mile northeast of Opal Camp. Most of these deposits contain a few objectionable nodules.

Many masses of perlite lie close to Opal Mountain. The basal 20 feet of the southwesterly dipping flow-breccia that forms the bulk of Opal Mountain consists of relatively pure perlite. The perlite is prominently exposed on the steep north and southeast slopes of the mountain for a distance of over a mile. It rests on a white lithic tuff. The southeast slope has been prospected, and a small amount of perlite has been taken from several pits.

Perlite also occurs at the top of the rhyolite flow-breccia previously mentioned, one deposit a mile south of the peak and another a mile northwest. Both deposits are about 50 feet thick but both contain chalcedonic nodules. The south deposit has been prospected by scraping and a small amount of perlite has been removed.

A mile north of Opal Mountain is a small rhyolitic plug. A zone of perlite up to 50 feet thick borders the east side of it. A larger plug 1 mile northeast of Opal Mountain has a 20-foot-wide zone of perlite along its south margin.

Gravel Hills

At the northwestern base of Hill 3851, which is made up largely of red rhyolitic breccia, is an irregular mass of perlite that has not been prospected. In the western Gravel Hills 3 miles northeast of Fremont Peak are numerous perlite zones associated with rhyolitic plugs or with red flow-breccia. Several of these form zones as much as 20 feet thick at the base of the red flow-breccia; others, up to 30 feet wide, occur at the margins of several plugs. These deposits have been prospected by digging several small pits.

Williams Plain

Near the Williams pumicite pit in secs. 7,8,17,18, T. 32 S., R. 46 E., the basal part of the thick flow-breccia contains discontinuous masses of perlite up to 30 feet thick. These have not been worked.

Two miles northeast of Coolgardie Camp, just west of the Goldstone road, a zone of perlite about 15 feet wide crops out at the south margin of a rhyolitic plug. A small tonnage has been dug from it.

Pumicite

Williams Quarry. This property is located in secs. 7,8,17,18, T. 32 S., R. 46 E., 6 miles east of Opal Mountain. The quarry was opened in 1947, and several thousand tons of pumicite have been removed. The operator is F. M. Williams, Star Route, Barstow, California.

Pumicite occurs in the Pickhandle Formation that in this vicinity strikes northwest and dips moderately northeast. In the vicinity of the quarry the formation consists of 500 feet of white to rusty-orange tuff. This rests on quartz monzonite and is overlain by rhyolitic flow-breccia that contains some perlite at the base. The lower portion of the tuff is light tan and sandy and contains no notable deposits of pumicite. The upper portion is white to rusty-orange and contains pumice. The marketable pumicite is confined to two layers separated by about 20 feet of tuff-breccia. The lower layer is about 12 feet thick and the upper layer is about 70 feet thick. Overlying the upper pumicite is 30 feet of tuff-breccia containing no pumicite and this in turn is overlain by rhyolitic flow-breccia.

The gray-white pumice layers can be traced for a mile or more. Both consist of angular pumice fragments that range in diameter from a fraction of an inch to several inches. The matrix is loosely consolidated pumicite.

Most of the pumicite marketed has been taken from a single pit in the thicker layer. The material is screened at the quarry into two sizes—plus 3/32-to-minus-½-inch and minus 3/32-inch (Wright, et al., 1953, p. 190).

Four miles south of the Williams pit is a small exposure of pumice-bearing white tuff resting on granitic rocks and overlain by Quaternary gravel. A small amount of pumicite has been taken from this deposit.

Ornamental Stone

Agate Nodules

The spherulitic nodules that contain fillings of chalcedony and/or agate occurring in the transitional zone between vitreous rhyolitic rock and perlite in the Opal Mountain volcanic field have for many years been collected by rockhounds and worked into beautiful specimens. The nodule matrix is of fine-granular, non-porphyritic texture, and of various blends of brown, pink, gray, and green. It is so highly silicified that it takes a polish equal to that of the chalcedony or agate interiors.

The once-hollow interiors are usually filled with chalcedony or agate, sometimes interlayered with white opal or quartz. The interior fillings are of many patterns, varying from irregular through star shaped to lens shaped. In many, the walls of the original cavity are partly or intricately brecciated and the spaces have been filled with clear chalcedony. The chalcedony-filled interiors of some nodules have been broken by later fractures that were again filled with chalcedony.

The chalcedony of the nodules of this volcanic field is either colorless or clear brown and is usually without banding, although in some nodules the chalcedony has faint banding concentric to the walls of the filling (agate), and in others has parallel straight banding across the filling (onyx). In a few nodules the chalcedony contains small patches of translucent to opaque orange or pink jasper.

Agate Nodule Localities. Most of the chalcedony-agate filled nodules are in the Opal Mountain volcanic field. The most prolific localities are three at or near Opal Mountain. The largest of these is a mile south of Opal Mountain Peak; another is a half mile down the northwest slope of this peak, and the third is a mile northwest of the peak. In all of these localities irregular-shaped chalcedony-agate-filled nodules weather out of decomposed perlite associated with the rhyolitic flow-breccia that forms Opal Mountain, or from perlite associated with small rhyolitic intrusions.

Less prolific localities of chalcedony-agate-filled nodules are found a mile east of Opal Camp; in Black Canyon at the low hill just east of the Hicks perlite quarry; and in another low hill a mile northwest of this quarry. In all of these localities the nodules are similar to those around Opal Mountain, and are in perlite adjacent to intrusive masses of brecciated rhyolitic rock.

The Gravel Hills volcanic field contains only rare occurrences of chalcedony-filled nodules. The only notable occurrence is near the southwestern base of the Gravel Hills 3 miles east-northeast of Fremont Peak, where a few nodules containing chalcedony were found in a mass of perlite on the western margin of a large rhyolitic plug.

Jasper

The rhyolitic rocks of the Opal Mountain Volcanics contain practically no jasper. However, colored jasper occurs in some of the Miocene basalt flows within the Pickhandle tuff and Barstow Formations or in rocks associated with the basalt flows.

The most prolific jasper locality is on a ridge a mile southwest of Opal Mountain. In this locality the jasper is in ferruginous silicified limestone and ferruginous chert that overlies the basalt flow within the Pickhandle tuff. The jasper is merely chert impregnated with iron oxides, chiefly red hematite and ochre-yellow limonite, probably derived from the underlying basalt flow. The jasper occurs in layers and veinlets from a fraction to several inches thick, and colors range from browns, reds, ochre-yellows, and greens, in various hues and blends, and in beautiful patterns that vary from layered, veined, mottled to sub-mossy. Most of the jasper forms a ledge 2 feet thick above the basalt, and crops out on top of a ridge, but the most colorful jasper occurs as fragments on the northeast slope of this ridge.

The red, weathered basalt exposed near the Opal Mountain road 1⅔ miles southeast of Opal Mountain contains veinlets a fraction of an inch to 2 inches thick. Red, yellow, and green mottled and mossy jasper, together with chalcedony, opal, and some calcite is found in those veinlets.

In lower Black Canyon, NE¼ sec. 21, T. 32 S., R. 44 E., the most southerly outcrop of Miocene basalt in the Barstow Formation contains veinlets, as thick as 2 inches, of yellow, green and red jasper. Most of this material contains large amounts of partly silicified iron oxides and therefore does not take a high polish.

Colored jasper and chert occur as occasional, scattered float in the volcanic gravels of the Barstow Formation westward from Black Canyon. Although most of this material is low grade, a careful search occasionally reveals colorful specimens.

Opal

At Opal Camp, or Scouts Cove, SE¼ sec. 36, T. 31 S., R. 44 E., 2 miles northwest of Opal Mountain, opal occurs as numerous veinlets less than a quarter of an inch thick in white lithic tuff of the Pickhandle Formation. All the opal now exposed is a translucent honey-yellow color, and some is quite clear. It is said that some fire opal was found here years ago. Prospects consist of two vertical shafts about 50 feet deep sunk on the opal-bearing tuff.

Saline Deposits

Small deposits of alkali salts occur as thin encrustations on the surface of Harper Dry Lake and on exposures of clay shales of the Barstow Formation in Black Canyon and in the Mud Hills. None of these is of commercial value, and commercial deposits have not been revealed by drilling.

Saline Deposits of Harper Dry Lake. The southeastern part of Harper Dry Lake, near Blacks Ranch, is generally moist. The mud of this part is alkaline and is covered in part by a thin saline crust. The crust is a fraction of an inch to nearly an inch thick, and the alkali becomes soft and powdery when dry. This saline crust forms on the surface as moisture in the mud rises to the surface and evaporates. The mud itself below the surface generally contains much alkali. The alkali mud generally has a smooth flat surface and is hard and cracked when dry, but, in places, portions of it rise a few inches above the smooth surface. This rising alkali mud is described by Thompson (1929, p. 269) as "self-rising ground" and according to analyses contains more salts than the smooth ground. Thompson (1929, p. 269) attributes this "self-rising" mud to rapid discharge and evaporation of ground-water at certain places on the mud flat. The chemical composition of the salts in the surface mud of Harper Dry Lake corresponds generally to the dissolved salts present in well water of Harper Valley, being mainly chlorides, carbonates and sulfates of sodium.

Analyses of alkali mud from sec. 30(?) T. 11 N., R. 3 W., eastern Harper Lake (Thompson, 1929, p. 67). (Figures indicate percent)

	Hard cracked mud				Self-rising ground	
Ca	Tr	Tr	Tr	Tr	.05	.05
Na and K	.87	2.82	.97	3.10	6.99	2.43
CO_3	.10	.72	.17	.06	.81	.78
HCO_3	.22	.38	.32	.18	.54	.28
SO_4	.46	1.02	.20	3.16	3.88	.47
Cl	.76	2.50	.96	2.26	6.70	2.40
B_2O_3	--	--	--	--	.10	--
NO_3	Tr	.02	.01	Tr	Tr	.02
Total	2.41	7.46	2.62	8.76	19.11	6.43
Depth	0–2″	2.6″	12″	0–1″	below 12″	0–2″

At the southwestern margin of Harper Lake mud flat are large ponds of alkali water and the surface of the mud surrounding them is generally covered with a crust of alkali. These saline ponds are not of natural origin. The alkali water is outflow via tiled ditches from the irrigated fields of Lockhart Ranch. The water was pumped from the deep wells on the ranch and used to flush out alkali from the soil of the fields where the alkali soil is underlain by clay.

The surfaces of Harper Dry Lake contain no saline deposits of commercial value, nor do the surface muds contain appreciable amounts of salines of economic value such as salts of potassium, lithium, boron, strontium or nitrogen. Only traces of borate salt in the form of ulexite have been found in the superficial mud on the north side of Harper Dry Lake.* It is unlikely that Harper Dry Lake contains any buried saline deposits, as four out of five test holes drilled on or near this playa (for logs see "Petroleum and Gas") penetrated Cenozoic strata to crystalline bedrock without encountering any saline layers.† Many water wells drilled southwest and southeast of Harper Dry Lake likewise did not encounter any saline deposits.

Saline Crusts on Lake-Bed Clays of Barstow Formation. In the Black Canyon anticline west of lower Black Canyon, sec. 16, T. 32 S., R. 4 E., a saline crust commonly occurs on the outcrops of the lake-bed clays of the lower part of the Barstow Formation. The saline crust is a white powdery material and is from a fraction to about an inch in thickness, and lies at or just below the surface of the thin residual clay soil that covers the clay exposures. The crust is composed mainly of thenardite (sodium sulfate) and contains 0.15 to 0.43 percent ulexite (sodium-calcium borate).‡ This saline material was deposited in the thin residual soil at the surface of the lake-bed clay exposures by moisture rising from the lake clays in which the sodium sulfate and borate salts are disseminated, as indicated from analyses of the clays,‡ and evaporating as it reaches the surface.

Similar saline crusts occur on exposures of lake-bed clays in the Barstow Formation of the Mud Hills, although these crusts are only a fraction of an inch thick. These have not been analyzed but presumably are composed mainly of sodium sulfate and sodium carbonate.

Borate

In 1955 three test holes drilled by the U.S. Geological Survey encountered a small deposit of the calcium borate colemanite under the alluviated flat north of Four Corners (or Kramer Junction), 2 to 3 miles northwest of the southwest corner of the Fremont Peak quadrangle. The colemanite was encountered as thin layers, from a fraction of an inch to several inches thick, in lake bed shales. It was found distributed in as much as 76 feet of shale, in a concentration up to 20 percent, and was found at depths of 1,020 to 1,460 feet (W. C. Smith, 1958, p. 26). The shale unit containing the colemanite is believed to be the same or approximately equivalent to the lake bed shale that contains the borates of the Kramer borate mines north of Boron described by Gale (1946, p. 340–346) north of Boron, 8 miles west of the Four Corners discovery. The results of this discovery are being prepared for publication by the U.S. Geological Survey. This discovery was followed by the drilling of a number of test holes in that area by private operators. Although the exact limits of the colemanite deposit are still to be determined, test holes drilled to date indicate that the extent of the deposit is small, probably not more than 500 acres, and the grade is subcommercial as of now.

As a result of this discovery, four test holes were drilled in 1956 by the Kerr-McGee Oil Company in T. 11 N., R. 6 W., in or near the extreme southwestern part of the Fremont Peak quadrangle. The locations of those within the area are shown on the map, plate 1. None of the four wells encountered borates. Three holes were drilled west of the southwest Lockhart fault and encountered shale below the older alluvium. The other hole to the east encountered only sand and gravel to bottom.

Petroleum and Gas

Prospecting for petroleum and gas has been carried on for many years in Harper Valley, and five unsuccessful test holes were drilled to depths varying from 450 to 2,468 feet. Several others were drilled in Harper Valley just beyond the south border of the map area as reported by Bowen (1954, p. 181–182). Harper Valley, as well as the entire mapped area, is not favorable for the occurrence of petroleum because neither within nor near the mapped area are there any marine source beds within the Tertiary series, and the pre-Tertiary sedimentary formations are too severely metamorphosed to contain any oil.

Chances for methane gas probably are equally unfavorable, although it is possible that a little gas could have formed from organic matter in lake beds of the Barstow Formation and might have accumulated in porous sands of this formation under favorable structural or stratigraphic conditions. About the only closed structure that might contain a little gas is the Black

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* Gale, H. S., Abstract of data on hand relative to borate deposits in the southwestern United States; unpublished manuscript, p. 102.

† R. L. Triplett, oral communication, 1950.

‡ Byers, F. M., and Dibblee, T. W., Jr., Status of borate exploration, western part of Barstow basin, California. U.S. Geol. Survey, unpublished manuscript.

Canyon anticlinal dome. Gas might be looked for in any porous sands of the dome that may be present in the lake bed clays at the structurally high point. The possibility that gas might also be found in sands within or just above lake bed clays at the western part of this anticline could be investigated best as follows: (1) west of the northwest-trending fault that cuts it, and (2) at the east end (east of lower Black Canyon and south of Black Mountain peak and east of the northwest-trending fault that cuts this anticline). The lake beds of the Black Canyon anticline probably are underlain by the Pickhandle tuff, which is unfavorable for the occurrence of gas.

The locations of the test holes drilled in Harper Valley are shown on Plate 1, and are listed in the accompanying table. It may be noted that the basalt encountered in most of these wells (first basalt in Harper Lake No. 2) is probably the Black Mountain Basalt; the alluvial sediments above it are Quarternary deposits; and the sediments below it are probably the Barstow Formation. Nothing comparable to the Pickhandle Formation was encountered in any of these drill holes. (Well No. 3 was located but never drilled.)

Summary logs of test holes drilled in Harper Dry Lake. (Drilled by and logs supplied by R. L. Tripplett, 1952; permission to publish by R. L. Tripplett).

Harper Lake No. 1, Sec. 27, T. 11 N., R. 4 W.
Depth—450 ft., drilled in 1949.

0– 125 ft.	clay
125– 328	clay and sand
328– 410	clay (boulders from 377 to 380 feet)
410– 450	gneiss or schist

Harper Lake No. 2, Sec. 8, T. 11 N., R. 3 W.
Depth—1,117 ft., drilled in 1949.

0– 35 ft.	sand
35– 125	clay
125– 322	sand
322– 330	clay
330– 470	sand and gravel
470– 614	basalt
614–1083	clay, sand, gravel
1083–1104	basalt
1104–1117	clay

Harper Lake No. 4, Sec. 4, T. 11 N., R. 4 W.
Depth—1,112 feet. Drilled in 1950.

0– 7 ft.	clay
7– 50	sand
50– 90	clay
90– 115	sand-gravel
115– 384	clay
384– 442	basalt
442– 685	clay
685– 788	red clay and boulders
788– 957	black sandstone—includes basalt?
957–1020	pink sandstone and clay
1020–1111	gravel-sand
1111–1112	basement complex

Harper Lake No. 5, Sec. 23, T. 11 N., R. 4 W.
Depth—830 feet. Drilled in 1952.

0– 487 ft.	sand and clay
487– 670	basalt
670– 830	gneiss

The following data on the four test holes drilled in T. 11 N., R. 6 W., S.B.B. & M., are taken from logs furnished by Dennis J. Ryan, geologist with Kerr-McGee Oil Industries, Inc., of Oklahoma (written communication, December 12, 1958; permission to publish by Kerr-McGee Oil Industries, Inc.), and is also the result of examination of the cores by the author accompanied by Mr. Ryan on January 26, 1959.

KERR-McGEE DRILL HOLE B-1

Date drilled: March 21–25, 1958.
Location: 300 ft. N. and 300 ft. W. of SE. cor. Sec. 24.
Elevation: 2,430 ft. Depth: 1,400 ft.
Interval cored: None.
Log:

0–1400 ft.	Light-gray to light-brown, fine-to-coarse-grained sand with some granitic pebbles.

Author's note: Entire section penetrated is probably Quaternary older alluvium.

KERR-McGEE DRILL HOLE B-2

Date drilled: March 26–April 1, 1958.
Location: 2,640 ft. N. and 600 ft. E. of SW. cor. Sec. 25.
Elevation: 2,425 ft. Depth: 856 ft.
Interval cored: 715 to 740 ft.; 800 to 856 ft.
Log:

0– 560 ft.	Cuttings of light brown, fine- to very coarse-grained sand, with pebbles above 390 feet.
560– 675 ft.	Cuttings of light-brown, fine-grained sand and green shale.
675– 715 ft.	Dark greenish-gray clay pebble conglomerate.
715– 718 ft.	Sticky light green to reddish brown sticky shale.
718– 740 ft.	Brownish black conglomerate. Pebbles are subrounded and as large as 1½ inch across; most are of very fine-grained diabasic basalt; a few are of light green to light purple shale. Intervals of light green to light purple shale cored from 725 to 729 ft.; 730 to 736 ft.; and 738 to 740 ft.
740– 800 ft.	Cuttings of sandy dark green to bluish gray shale.
800– 803 ft.	Dark-greenish and reddish-brown indurated sandstone containing small pebbles of shale and of diabasic basalt.
803– 856 ft.	Greenish-black hard, fine- to medium-grained sandstone, in places conglomeratic, with fragments of diabasic basalt, granitic rock and hard shale. Dip of bedding 60° to 75°. Numerous slippage planes coated with calcite. Below 854 ft. contains pebbles of diabasic basalt as large as 3 inches in diameter.

Author's note: Section from surface to 560 ft. is probably Quaternary older alluvium, and 560 to 856 ft. is probably Tertiary.

KERR-McGEE DRILL HOLE B-3

Date drilled: April 7–18, 1958.
Location: 3,000 ft. N. and 600 ft. E. of SW. corner Sec. 22 (just beyond western border of Fremont Peak quadrangle).
Elevation: 2,540 ft. Depth: 914 ft.
Interval cored: 480 to 914 ft.
Log:

0– 480 ft.	Cuttings were granitic sand and silt, and pebbles of chert and quartz monzonite.
480– 500 ft.	Light-gray fine- to medium-grained micaceous sandstone with scattered pebbles of quartzite and quartz monzonite. Thin layers of shale below 498 ft.
500– 685 ft.	Light-green to gray shale, micaceous siltstone and interbedded light-brown fine- to coarse-grained arkosic sandstone. Light-brown, gritty pebble conglomerate at 510-14 ft. containing grit and pebbles of granitic material as large as ½ inch across; gray tuffaceous sandstone at 592–97 ft. and 625–29 ft.; dip of bedding, 20° at 514 ft., 23° at 620 ± ft.
685– 796 ft.	Interbedded dark-gray to light-green shale, micaceous siltstone, gray to black fine- to coarse-grained micaceous arkosic to muddy sandstone. Sandstone contains angular pebbles of granitic rock and of weathered diabase at 671–81 ft., 720–24 ft., and 744–68 ft. Bedding dip of 45° ± at 760 ± ft.
796– 855 ft.	Gray to green shale and siltstone. Bedding dip of 27–30° at 824 ± ft.

855– 914 ft.	Interbedded light green shale, siltstone, muddy fine- to medium-grained sandstone, and dark gray to black pebble conglomerate of granitic fragments as large as ¼ inch across. Bedding dip of 31° at 910 ± ft.

Author's note: Section from surface to 500 ft. is probably Quaternary older alluvium; 500 to 914 ft. is probably Tertiary sedimentary rocks.

KERR-McGEE DRILL HOLE B-4

Date drilled: April 18–27, 1958.
Location: 2,640 ft. S. and 500 ft. E. of NW. corner Sec. 26.
Elevation: 1,755 ft. Depth: 1,629 ft.
Interval cored: 1,590 to 1,629 ft. and 1,652 to 1,668 ft.
Log:

0– 95 ft.	Cuttings of fine to coarse brown sand with some granitic pebbles.
95–1590 ft.	Cuttings of fine- to coarse-grained granitic sand, pebble and boulder fragments.
1590–1595 ft.	Dark greenish gray sticky to hard shale; highly slickensided. Bedding dip, 30° ±.
1595–1668 ft.	Dark greenish-gray fine- to coarse-grained arkosic sandstone containing quartz monzonite pebbles as large as 2 inches diameter; poorly sorted, weakly indurated; some dark gray biotitic siltstone below 1,652 ft.
1668–1703 ft.	Cuttings of greenish-gray, fine- to coarse-grained sandstone.
1703–1755 ft.	Cuttings of granitic sand and quartz monzonite boulder fragments; drilling exceedingly difficult.

Author's note: Base of Quaternary older alluvium is either in uncored interval above 1,590 ft., or below bottom of this hole.

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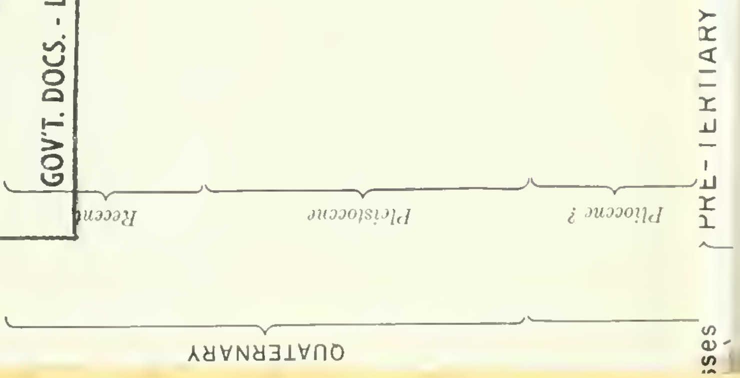

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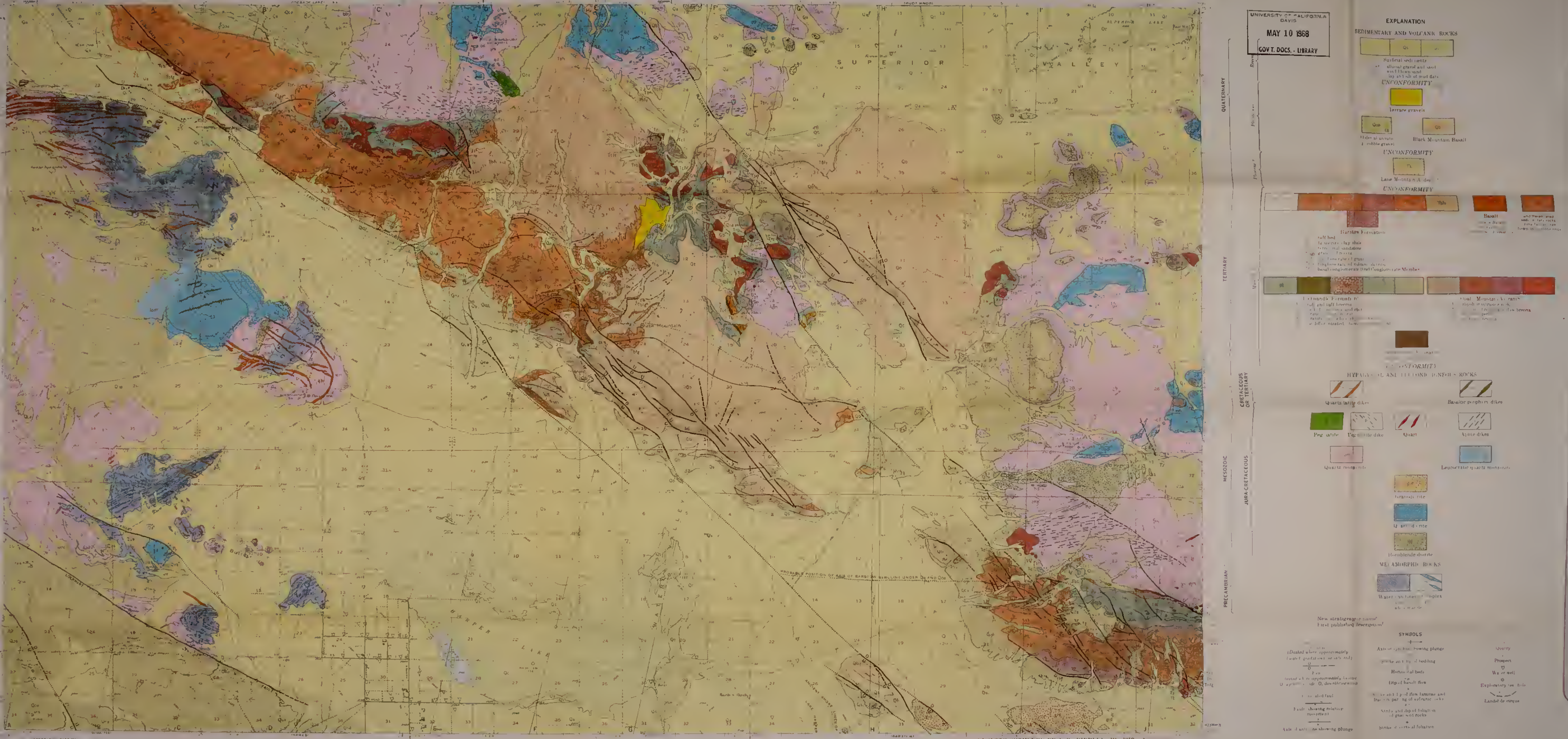

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GEOLOGIC AND ECONOMIC MAP OF THE FREMONT PEAK AND OPAL MOUNTAIN 15 MINUTE QUADRANGLES, SAN BERNARDINO COUNTY, CALIFORNIA

BY T. W. DIBBLEE JR

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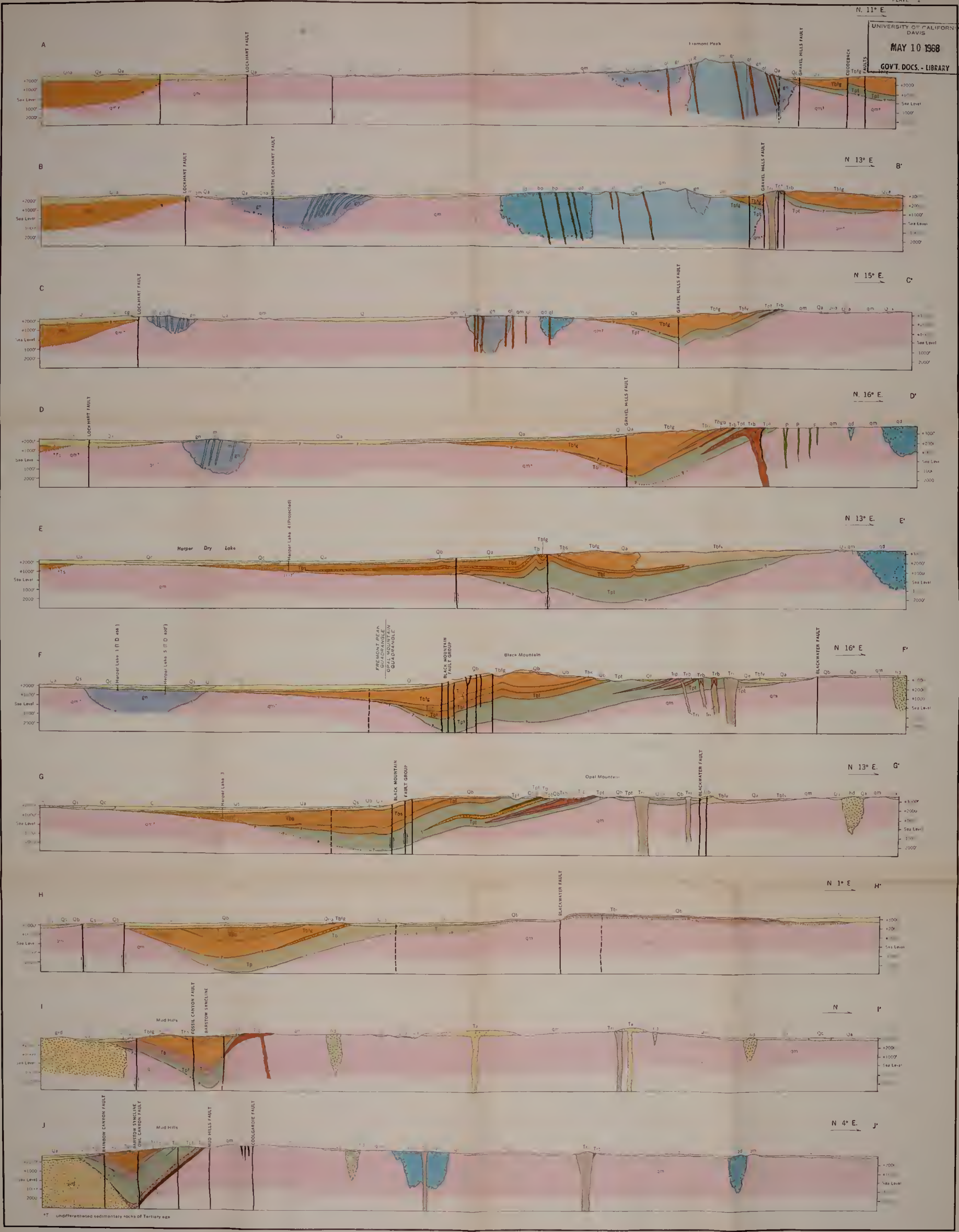

STRUCTURE SECTIONS OF THE FREMONT PEAK AND OPAL MOUNTAIN 15-MINUTE QUADRANGLES, SAN BERNARDINO COUNTY, CALIFORNIA

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GEOLOGIC MAP
OF THE
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SAN BERNARDINO COUNTY, CALIFORNIA

Geology by T.W.Dibblee Jr., 1951
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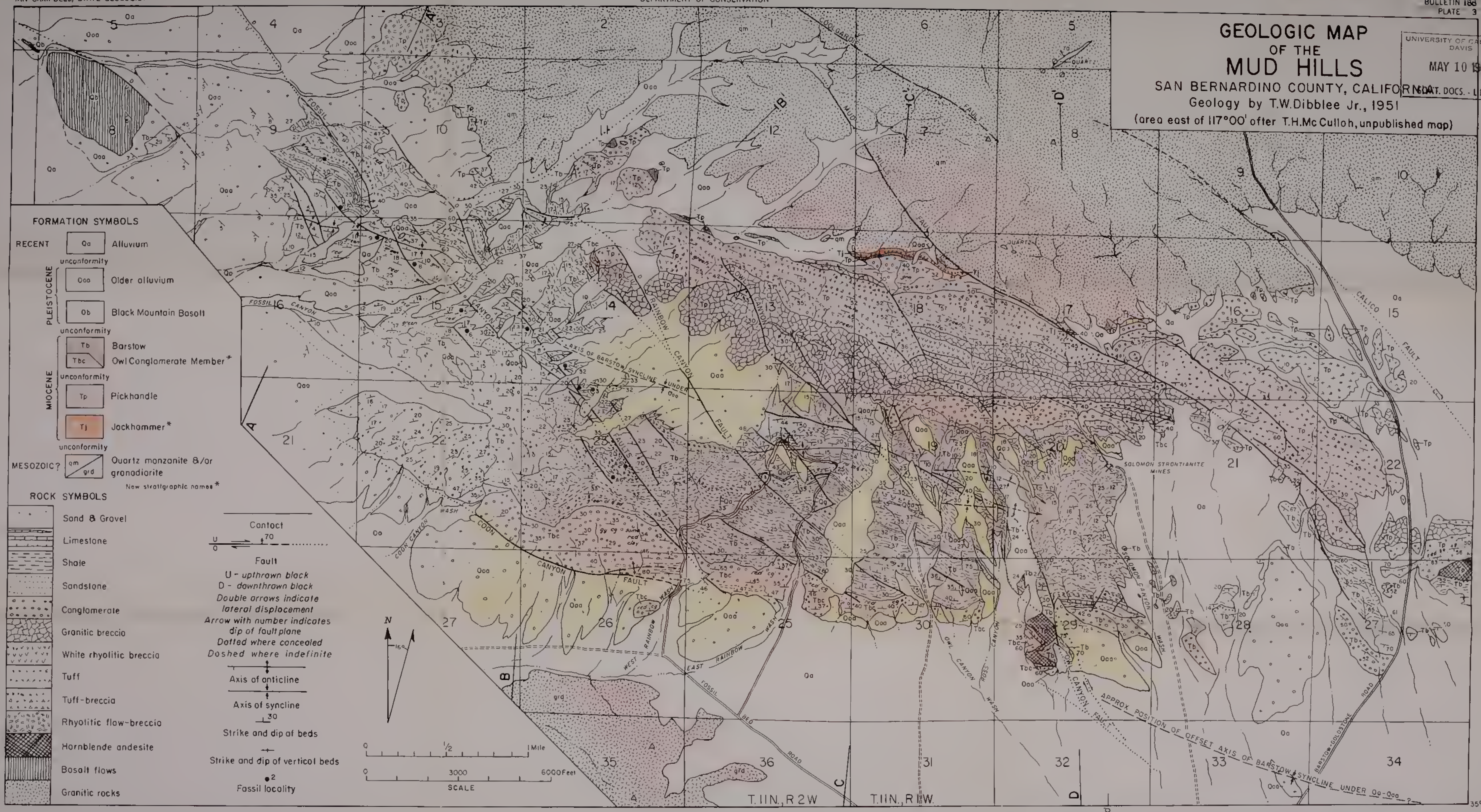

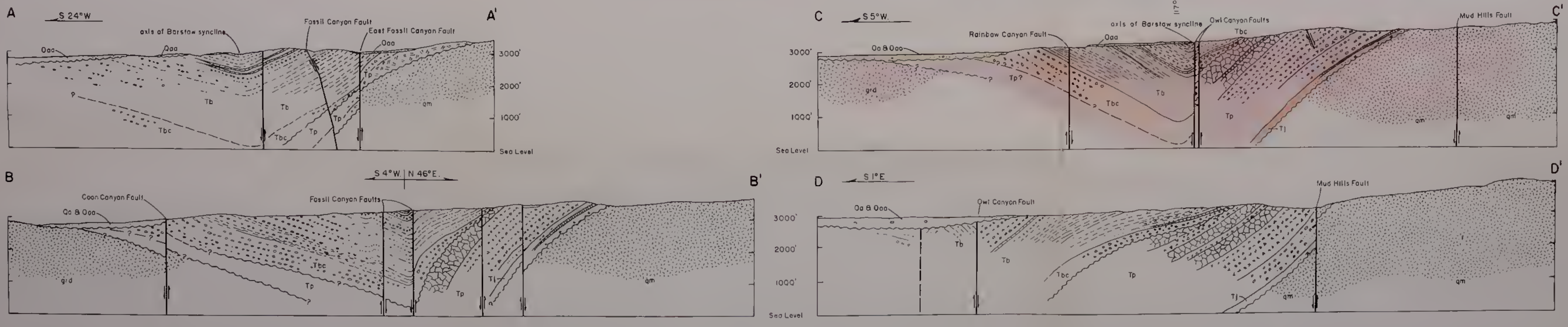

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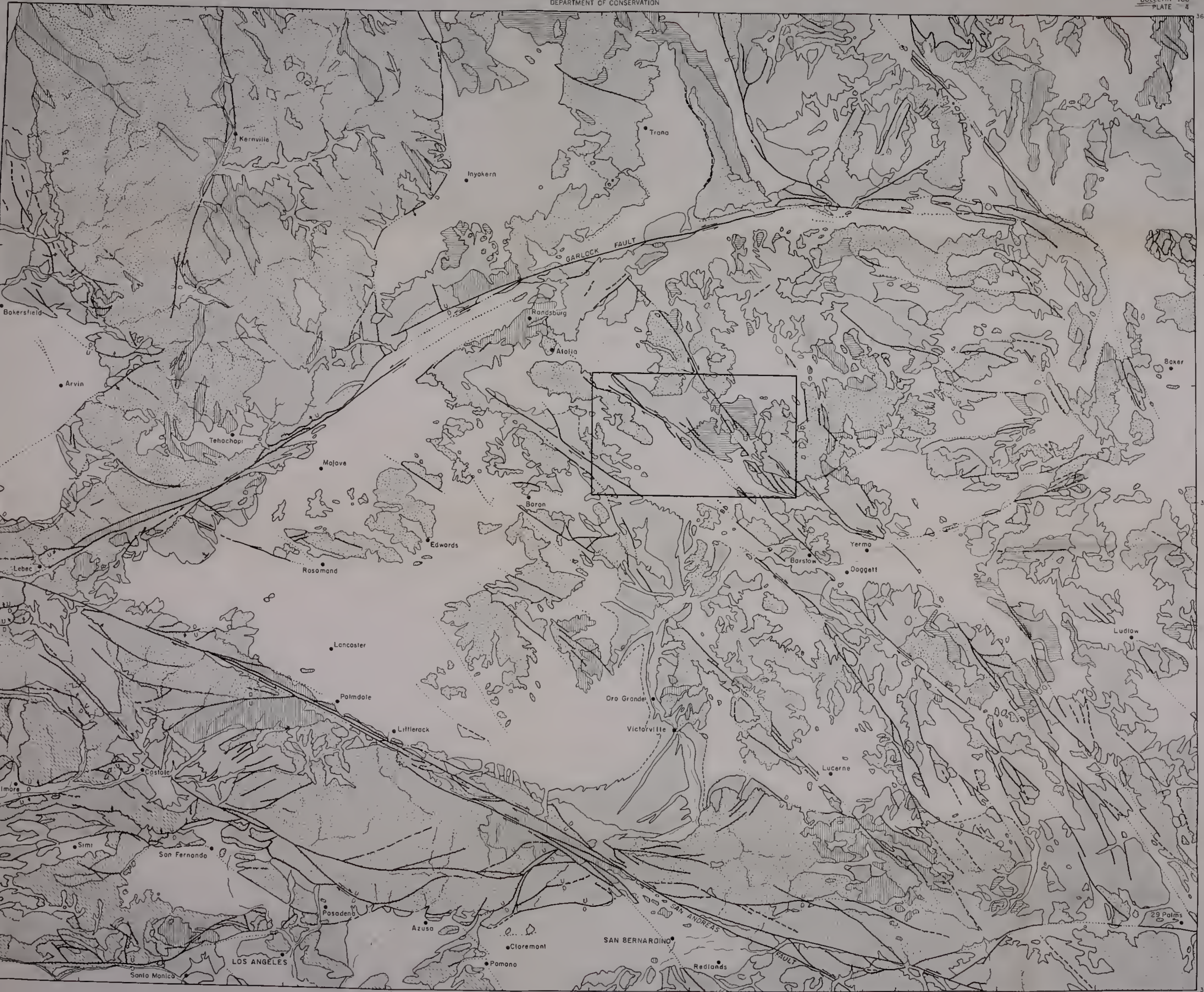

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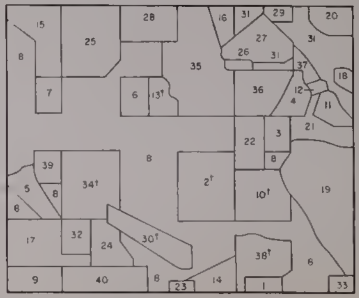
GENERALIZED GEOLOGIC MAP OF THE MOJAVE DESERT REGION, CALIFORNIA, SHOWING GEOLOGIC SETTING OF FREMONT PEAK AND OPAL MOUNTAIN QUADRANGLES (IN HEAVY OUTLINE)

EXPLANATION

Recent	▭	Alluvium	QUATERNARY
	▨	Playa clay	
Pleistocene	▨	Gravel and sand	
	▨	Basalt	
	▭	Non marine sedimentary and volcanic rocks	TERTIARY
	▨	Marine sedimentary rocks	
	▨	Marine sedimentary rocks	CRETACEOUS
	▥	Metasedimentary rocks	PRE-CRETACEOUS
	▨	Plutonic and hypabyssal rocks (including gneisses and metavolcanic rocks)	PRE-TERTIARY

------- Contact, dashed where indefinite

U D ——— Fault, dashed where approximately located, dotted where concealed; U, relatively upthrown block, D, relatively downthrown block; double arrows indicate relative strike-slip displacement; arrow on fault indicates dip of fault plane



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* Field checked and modified by T W Dibblee Jr